ADVANCED FUEL CYCLE INITIATIVE (AFCI)

PROGRAM PLAN

January 30, 2004

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Acronyms and Symbols

ADS	accelerator-driven system
AFC	Advanced Fuel Cycle?
AFCI	Advanced Fuel Cycle Initiative
AGR	Advanced Gas Reactor
ALWR	advanced light water reactor
Am	americium
An	actinide
ANL	Argonne National Laboratory (Chicago)
ANTT	Advanced Nuclear Transformation Technology
ATR	Advanced Test Reactor (INEEL)
BNL	Brookhaven National Laboratory
BOL	Beginning of Life
CCD	chlorinated cobalt dicarbollide
CEA	Commissariat à l'Energie Atomique (France)
CERCER	ceramic-ceramic
CERMET	ceramic-metal
Cm	curium
Cs	cesium
CY	Calendar Year
CYANEX	cyanide extraction
DELTA	Development of Liquid Metal Technologies and Applications
DIAMEX	dianide extraction
DOD	Department of Defense
DOE	Department of Energy
EBR	Experimental Breeder Reactor
ENDF	Evaluated Nuclear Data File – Evaluations that can be used in MCNPX for more accurate predictions of fission, criticality, transport, and radiation damage
ESE	Engineering-Scale Experiment
Eu	europium
FCCI	fuel cladding chemical interaction
FDWG	fuel development working group
FFTF	Fast Flux Test Facility
FGR	Fast Gas Reactor
FY	fiscal year
Gen IV	Generation IV, the Generation IV Nuclear Energy Systems Program
GFR	Gas-Cooled Fast Reactor
GWe	gigawatts electric
HM	heavy metal
HQ	Headquarters
HTGR	High Temperature Gas Reactor
I	iodine
IAC	Idaho Accelerator Center
ICE	independent cost estimate
IMF	inert matrix fuels
INEEL	Idaho National Engineering and Environmental Laboratory
ITU	Institute for Transuranium Elements (Karlsruhe, Germany)
LANL	Los Alamos National Laboratory
LCC	liquid cadmium cathode
LLNL	Lawrence Livermore National Laboratory
LTA	Lead Test Assembly
LWR	light water reactor
MEGAPIE	Megawatt Pilot Experiment
MILE	mastering IMF in LWR environment
MIT	Massachusetts Institute of Technology

Mt	metric ton
N	nickel or nitride
NE	Office of Nuclear Energy, Science, and Technology
NERAC	Nuclear Energy Research Advisory Committee
NERI	Nuclear Energy Research Initiative
NGNP	Next Generation Nuclear Plant
NHI	Nuclear Hydrogen Initiative
Np	neptunium
NRC	Nuclear Regulatory Commission
NTD	National Technical Director
OCRWM	Office of Civilian Radioactive Waste Management
ORNL	Oak Ridge National Laboratory
PART	Program Assessment Rating Tool
PEG	polyethylene glycol
PHENIX	Fast Reactor in France
PIE	post-irradiation examination
PSI	Paul Scherrer Institute (Switzerland)
Pu	plutonium
PUREX	Plutonium-Uranium Extraction
PWR	Pressurized Water Reactor
PYRO	pyrochemical process
PYROX	pyrochemical oxidation
QA	quality assurance
R&D	Research and Development
SANEX	selective actinide extraction
SFTF	Spent Fuel Treatment Facility
SNF	spent nuclear fuel
SNL	Sandia National Laboratories
Sr	strontium
TBP	tri-*n*-butyl phosphate or tributylphosphate
TBD	to be determined
Tc	technetium
TRADE	TRIGA Accelerator Driven Experiment
TRIGA	Small Reactor Type
TRISO	Tri-isotropic, referring to a multi-layered fuel-particle coating consisting of pyrolytic carbon and silicon carbide
TRL	Technical Readiness Level
TRU	transuranics (americium, curium, neptunium, and plutonium)
TRUEX	aqueous solvent extraction process for TRU recovery
TRUMOX	transuranic mixed oxide
U	uranium
UFP	University Fellowship Program
UNLV	University of Nevada Las Vegas
URA	University Research Alliance
UREX	uranium extraction (an aqueous partitioning process)
VHTR	Very-High Temperature Reactor
WSRC	Westinghouse Savannah River Company
XADS	a European Commission ADS demonstration project
Zr	zirconium

1.0 EXECUTIVE SUMMARY

This document presents the ten-year program plan for the Advanced Fuel Cycle Initiative (AFCI). It summarizes the major program elements, key milestones and required budget through 2014 to achieve the program goals and objectives.

Research and development (R&D) is focused on developing and demonstrating technologies that would enable the transition to an environmentally, socially, economically, and politically acceptable advanced fuel cycle. With demonstrated technologies, options for alternative waste-management strategies can be explored with confidence.

The AFCI program is developing fuel systems for Generation IV reactors and is creating enabling fuel cycle technologies for current and future generation nuclear reactors, including Generation IV reactors, which can reduce high-level waste volume, increase the capacity of geologic repositories, and reclaim the valuable energy in spent fuel. Implementation of such advanced fuel cycles may delay or even eliminate the need for a second repository in the United States, while reducing the inventory of civilian plutonium. The quantities of certain mobile radionuclides in a repository can be reduced, as can the radiotoxicity of the waste.

Near-term program activities are designed to provide technical and economic data in support of a Secretarial report to Congress in the 2007-2009 time period on the need for a second repository. During that same period, the program will be evaluating the long-term role of transmutation in the management of nuclear waste, including the use of thermal and fast reactors, the design of transmutation fuels and the application of wet and dry chemical processing.

For AFCI to have a meaningful impact on the future of nuclear energy in the United States, the program has established the following objectives during the next ten years:

- **In FY 2008, provide preliminary engineering data and analysis to support the Secretarial Recommendation to Congress on the need for a second repository.** By this date, the program will provide a set of options that can preclude the need for a second repository for a very long time.
- **By 2010, quantitatively define the most technically feasible and desirable nuclear fuel cycle options and validate the new technologies necessary for their implementation during the transition to a stable long-term fuel cycle.** By achieving this objective, the program will have established credible and feasible fuel cycle technologies that can be used to transition to an advanced fuel cycle. This information will provide additional technical information for the Secretary's recommendation.
- **By 2012, complete the fuel qualification program the Next Generation Nuclear Plant**. Advanced particle fuels required for the Next Generation Nuclear Plant will be developed and qualified through a program of testing and analysis leading Nuclear Regulatory Commission (NRC) approval.
- **By 2015, develop engineering data to recommend the best option for transitioning nuclear waste management toward the future and obtain sufficient information to begin near-term implementation.** By achieving this objective, the program will have defined the separations system in sufficient detail that DOE could initiate the design of a spent fuel treatment facility.

- **By 2015, quantitatively define the most technically feasible and desirable long-term Generation IV nuclear fuel cycle option and validate the new technologies necessary for its implementation**. This objective marks the point in time where we have defined the preferred Generation IV fast reactor and fuel cycle in sufficient detail that the qualification of the fuel system required for the selected Generation IV systems could be initiated.

The work needed to accomplish these objectives is described in this program plan. Success in achieving the AFCI technical objectives will provide both economic and energy security benefits to the U.S. A preliminary analysis shows that implementing AFCI technologies could reduce the cost of the proposed Yucca Mountain repository by several billion dollars and significantly delay the need for a second geologic repository. Substantial net cost savings over the next 40 years are also projected. The energy value from spent nuclear fuel currently in storage could also be reclaimed leading to a decrease in civilian plutonium inventories.

In summary, the AFCI program will provide options for the management of spent nuclear fuel, through spent fuel treatment and transmutation, which will reduce the cost and hazards of repository disposal, reduce the amount of civilian plutonium accumulating in the nuclear fuel cycle, and recover unused fuel and its energy value from the waste.

2.0 OVERVIEW OF THE ADVANCED FUEL CYCLE INITIATIVE

2.1 Vision and Mission

Vision

The *National Energy Policy* issued by the Bush Administration in May 2001 recommended an expansion of nuclear energy in this country, development of advanced nuclear fuel cycles and next generation technologies, and development of advanced reprocessing and fuel treatment technologies. Recent studies by the Massachusetts Institute of Technology (MIT) and National Laboratory Directors have also emphasized the need for growth in nuclear power. To achieve this vision, the U.S. must be a worldwide leader in the development and demonstration of technical options that are used to:

1) Expand the use of nuclear energy worldwide,
2) Effectively manage radioactive waste,
3) Reduce the threat of nuclear material misuse, and
4) Enhance national security.

To address this challenge, the Office of Advanced Nuclear Research (DOE/NE-20) has adopted an integrated strategy consisting of the Generation IV Nuclear Energy Systems Initiative (Gen IV), the Nuclear Hydrogen Initiative (NHI), and the Advanced Fuel Cycle Initiative (AFCI).

Mission

The Generation IV-AFCI Integrated Program will develop the next generation of nuclear energy systems, capable of providing energy for generations of Americans, by:

- Developing and demonstrating advanced nuclear energy systems that meet future needs for safe, sustainable, environmentally responsible, economical, proliferation-resistant, and physically secure energy (Gen IV).
- Developing and demonstrating technologies that enable the transition to a stable, long-term, environmentally, economically, and politically acceptable advanced fuel cycle (AFCI).

Gen IV supports this mission through the development of innovative, next-generation reactor technologies. Within Gen IV, the Next Generation Nuclear Plant (NGNP) project will develop advanced high-temperature, gas-cooled reactor technology and demonstrate the capability of this technology to power the economic production of hydrogen and electricity. Gen IV will also invest in the development of next generation fast-neutron spectrum reactor technologies that hold significant promise for advancing sustainability goals and reducing nuclear waste generation. The integrated value to the nation of a new fleet of Gen IV reactors will far exceed that of today’s fleet.

Closely coupled to Gen IV is the Nuclear Hydrogen Initiative, which contributes to the integrated mission by demonstrating hydrogen production technologies using advanced high-temperature nuclear energy technology. This initiative will develop hydrogen production technologies that are compatible with nuclear energy systems and these will be validated through scaled demonstrations. A commercial-scale prototype demonstration plant could be coupled with a Gen IV demonstration facility by the middle of the next decade.

Achieving the vision of sustainable growth of nuclear energy in the U.S. will also require that our country transition from the current once through fuel cycle to an advanced fuel cycle. AFCI is a focused R&D program whose technologies will enable this transition in the most efficient manner. AFCI will develop fuel systems for Generation IV reactors and create enabling fuel cycle technologies (i.e., fuel, cladding, separations, fuel fabrication, waste forms, and disposal technology) to reduce spent fuel volume, separate long-lived, highly radiotoxic elements, and reclaim spent fuel's valuable energy. AFCI technologies will support both current and future nuclear energy systems, including Generation IV systems.

2.2 Transition to the Advanced Fuel Cycle

The DOE/NE vision for the long-term future of nuclear energy in the United States is shown in Figure 2-1. Programs such as NEPO, NP 2010, Generation IV, and the Nuclear Hydrogen Initiative are anticipated to extend the life of currently operating reactors and introduce successive generations of more advanced reactors to the U.S. energy infrastructure. As the number of deployed units increases, the demands a once-though fuel cycle place on the repository increase dramatically. The AFCI program works to counter this trend. In the intermediate term, introducing ultra-high-burnup-fuels and proliferation resistant recycle of Pu in thermal reactors can reduce the spent fuel accumulation rate, as compared to the once-through fuel cycle. In the longer term, a closed fuel cycle based on full actinide recycle can begin to actually decrease the spent fuel inventory due to efficient utilization of the spent fuel resource. In addition, the resulting high-level waste product bound for geologic disposal is dramatically less toxic than the spent fuel that would be disposed under the once-through cycle. This self-sustaining closed fuel cycle improves the acceptability of an increasing role for nuclear power.

Hence, while the future is uncertain, it is nevertheless highly probable that Light Water Reactors (LWRs) will continue to operate for many years in this country and Advanced Light Water Reactors (ALWRs) are likely to be ordered within the next decade. As a result, it is expect that the amount of LWR-type spent fuel is expected to grow for many decades beyond the scheduled opening of Yucca Mountain in 2010. Orders may occur as early as 2020 for the first Generation IV NGNP reactors and a decade or more later for Gen IV fast reactors. New fuel systems and fuel cycles will be required at that time. For this reason, a strategy that focuses solely on the end-state and neglects the transitional phase would not be robust. The AFCI strategy anticipates the transition from the current once-through fuel cycle to one that is progressively more sustainable over the next several decades. Technologies are being demonstrated and developed to support this transition.

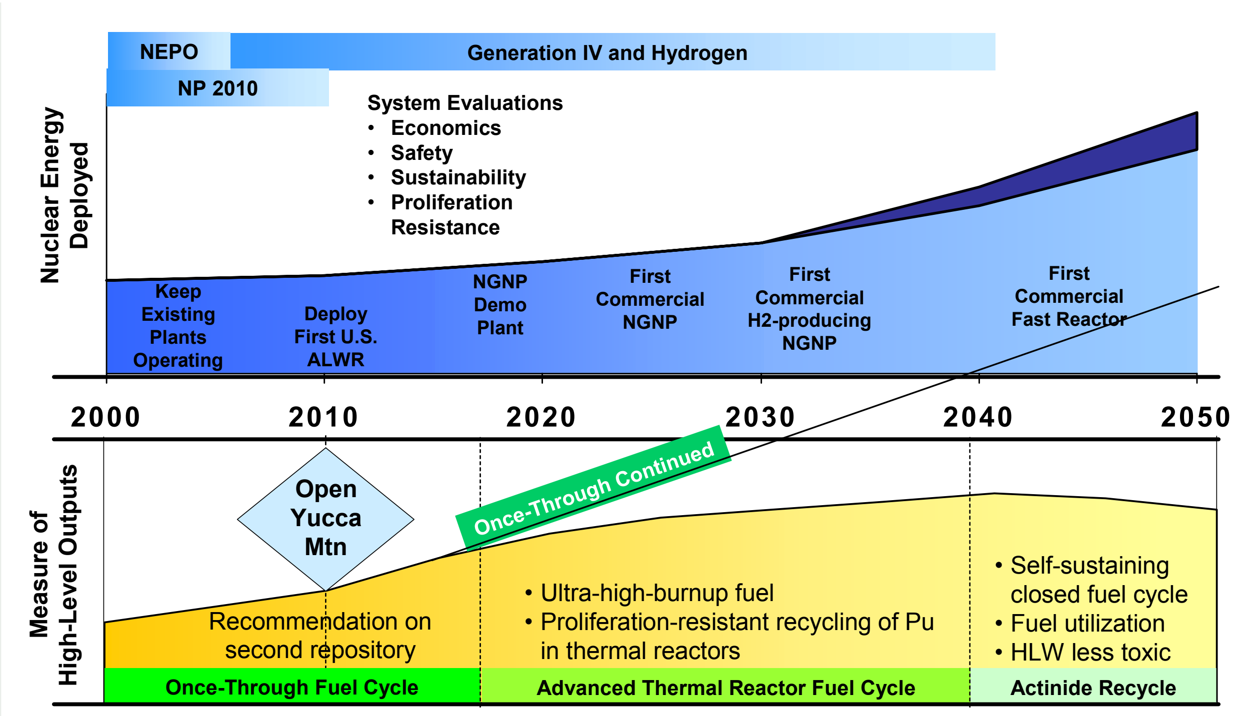

Figure 2-1. A Long-Term U.S. Strategy for Nuclear Energy

A major objective of the combined AFCI, NHI, and Gen IV programs is to define and implement a sustainable nuclear energy supply in the U.S. The system envisioned will make better use of natural resources and will generate significantly less waste than the current open fuel cycle. Sustainable systems have already been well explored within the AFCI program; consisting of a single stratum fast reactor system with a totally closed fuel cycle or a dual strata system that combine thermal and fast reactors. The transition from the current once-through fuel cycle to a closed fuel cycle is not yet fully understood, and it implies several levels of decision making: policy decisions (the start of a reprocessing enterprise), utility decisions (the conversion of existing plants to new fuel types and the purchase of new reactors), and technical decisions (the feasibility of advanced technologies).

A schematic of a possible transition is illustrated in Figure 2-2. The curves here indicate the behavior of the waste accumulation measure, ω, as a function of nuclear energy produced (Q) for three scenarios. The measure, ω, is itself a representation of a variety of quantities of interest including mass of spent fuel, mass of plutonium (a proliferation concern), short-term heat load (a handling concern dominated by fission products), long-term heat load (a quantity that determines the repository capacity dominated by minor actinides), dose, and radiotoxicity (quantities of societal and environmental concern dominated by a small number of fission product and transuranic isotopes). Five separate but overlapping phases are distinguished as follows:

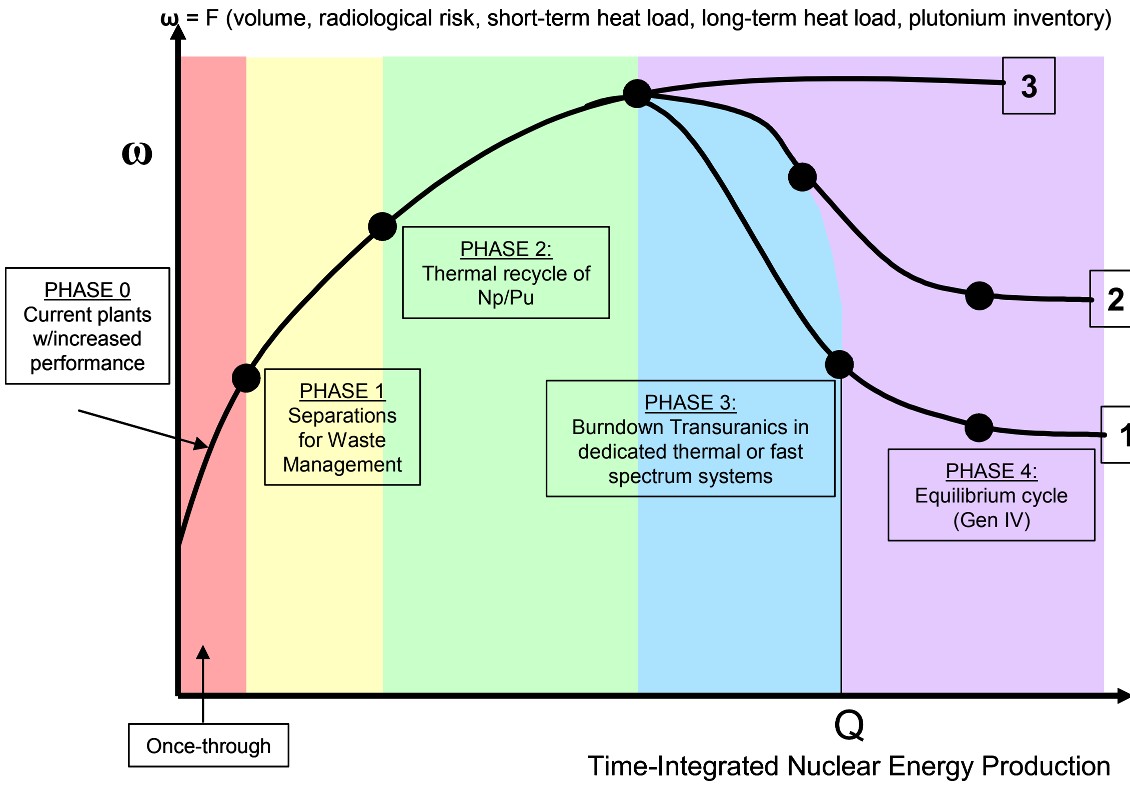

Figure 2-2. AFCI Phased Approach to a Closed Fuel Cycle

Phase 0 represents the current Spent Nuclear Fuel / High Level Waste accumulation phase, based on the once-through fuel cycle. LWRs continue operating at almost a constant power level and ALWRs begin to be introduced. Many of the quantities represented by ω increase at a roughly linear rate. It is expected that the rate of increase for most of these quantities could be reduced by 20% to 30 % by increasing the average burnup of LWR fuels from 50,000 to 100,000 MW-day per metric tonne.

Phase 1 represents the start of reprocessing operations, without recycling, and still only operating LWRs and ALWRs for nuclear energy generation. This phase focuses on fuel cycle processes that would benefit radioactive waste management and could begin in the second quarter of this century. Processes that assist in volume reduction and removal of the dominant short-term heat source would be candidates for deployment. Consequently, uranium, cesium, and strontium would be extracted from the spent fuel. These products would be stored separately from the remaining material. The remaining transuranics and fission products would then be packaged or stored for final disposal or future use. Therefore, the volume of spent fuel would be significantly reduced from the once-through operations; the separation and management of certain chemical elements might help reduce the short-term heat load burden on the repository; and the use of special waste forms could reduce the dose. However, radiotoxicity, long-term heat load (and consequently repository capacity) would remain unchanged.

Phase 2 represents the recycling of proliferation-resistant fuels containing Pu and other components of LWR spent-fuel in thermal reactors (existing LWRs, ALWRs, or high-temperature gas reactors (HTGRs)). Technologies for recycling plutonium in thermal reactors are quite well known, and it is expected that the use of existing or advanced recycling technologies could stabilize or even reduce plutonium stockpiles. The U.S. needs to develop proliferation-resistant variants of these technologies. Recycling minor actinides in these systems is not well understood, and practical difficulties are expected in implementing such technologies. Thus, it is not clear yet whether long-term heat load and radiotoxicity would be significantly impacted. However, it is clear that to have any significant impact, a large number of reactors using recycled fuel would be required.

Phase 3 represents a burn-down phase that would rely on either advanced thermal reactors for burning plutonium and a fraction of the minor actinides or fast reactors to burn all transuranics. Fast reactors could be dedicated burner machines (fast reactor or accelerator driven) based on advanced fuels technologies or Gen IV reactors using fuels that are more conventional. Again, a very significant infrastructure (reprocessing capacity and reactors) is needed to equilibrate and burn down stockpiles.

Phase 4 represents the equilibrium Gen IV scenario based on a self-sufficient combination of full actinide recycle and reactor systems that produce only minimal amounts of waste.

In summary, phases 0, 1, and 2 form a transitional period, focused on near to intermediate term objectives of:

- Reducing high-level waste volumes,
- Increasing the capacity of the planned geologic repository,
- Reducing the technical need for a second repository,
- Reducing long-term inventories of plutonium in spent fuel, and
- Enabling recovery of the energy contained in spent fuel.

Phases 3 and 4 have longer-term objectives of supporting the operation of the Generation IV fuel cycle and focus on:

- Reducing the toxicity of spent nuclear fuel,
- Reducing the long-term heat generation of spent nuclear fuel, and
- Providing a sustainable fuel source for nuclear energy.

Also shown in the Figure are the three curves that illustrate the effect on the measure ω for different approaches to waste management. The first curve (lowermost on the chart) assumes that nuclear energy production continues and no additional repositories, beyond Yucca Mountain, are deployed in the United States. For this case, an aggressive burn-down phase will be needed, using dedicated transmutation systems in the form of either Accelerator Driven Systems or low Conversion Ratio Fast Reactors, because the Spent Nuclear Fuel (SNF) accumulation will eventually exceed the Yucca Mountain capacity. This transition via aggressive burn-down must occur sometime in this century, before SNF inventories become unmanageable.

The third curve (uppermost) assumes that repositories are added as SNF inventories grow until a self-sustained nuclear energy phase is achieved via the introduction of Generation IV reactors. In this case, the strategy would be to slow the waste growth as much as possible until the equilibrium phase is reached. No dedicated transmutation systems are used to transition to the new cycle. As a result, with continued nuclear energy production, multiple repositories would be required.

The middle curve (curve 2) assumes an implementation decision between the two extremes. In this case, additional repository capacity is added during the century, but a more moderate burn-down strategy is used by deploying a smaller number of dedicated transmutation devices.

The actual path will depend on economics, policy decisions, and the growth or decline in nuclear energy production in the next few decades. In any case, the AFCI program is flexible and broad enough top cover the spectrum of possible outcomes.

2.3 AFCI Goals and Objectives

Implementation of AFCI technologies has the potential to reduce the cost of waste management, delay the technical requirement for a second geologic repository, and dramatically reduce the inventory of civilian plutonium in the U.S. while recovering the energy value from spent nuclear fuel. Because a Secretarial Recommendation regarding the need for a second repository is required in the 2007–2010 timeframe, the AFCI program will provide timely information to support waste management options.

For AFCI to have a meaningful impact on the future of nuclear energy in the U.S., the program has established the following success-oriented goals and objectives:

- **In FY 2008, provide preliminary engineering data and analysis to support the Secretarial Recommendation to Congress on the need for a second repository.** By this date, the program will provide a set of options that can preclude the need for a second repository for a very long time.
- **By 2010, quantitatively define the most technically feasible and desirable nuclear fuel cycle options and validate the new technologies necessary for their implementation during the transition to a stable long-term fuel cycle.** By achieving this objective, the program will have established credible and feasible fuel cycle technologies that can be used to transition to an advanced fuel cycle. This information will provide additional technical information for the Secretary’s recommendation.
- **By 2012, complete the fuel qualification program the Next Generation Nuclear Plant**. Advanced particle fuels required for the Next Generation Nuclear Plant will be developed and qualified through a program of testing and analysis leading Nuclear Regulatory Commission (NRC) approval.
- **By 2015, develop engineering data to recommend the best option for transitioning nuclear waste management toward the future and obtain sufficient information to begin near-term implementation.** By achieving this objective, the program will have defined the separations system in sufficient detail that DOE could initiate the design of a spent fuel treatment facility.
- **By 2015, quantitatively define the most technically feasible and desirable long-term Generation IV nuclear fuel cycle option and validate the new technologies necessary for its implementation**. This objective marks the point in time where we have defined the preferred Generation IV fast reactor and fuel cycle in sufficient detail that the qualification of the fuel system required for the selected Generation IV systems could be initiated.

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3.0 BACKGROUND

The *National Energy Policy* recognizes that nuclear energy should play an important role in the future of the nation's energy security needs. Nuclear power is the only available technology that can produce economical quantities of baseload energy without emitting harmful pollutants, including those associated with global climate change. Currently, nuclear energy currently produces one-fifth of all electric power in the U.S.

Of the issues affecting future expansion of nuclear energy in the U.S. and worldwide, none is more important or challenging than implementing an effective nuclear fuel cycle. Nuclear power plants produce far less waste than any comparable energy producing or industrial activity. However, the nature of spent nuclear fuel requires long-term planning to include consideration of potential reuse and disposal. Disposal of this material, which remains highly radioactive for hundreds of thousands of years, presents a wide range of technical, regulatory, social, and political issues.

The U.S. currently stores more than 46,000 metric tons (Mt) of spent nuclear fuel at commercial nuclear power plants, and the ~103 operating reactors generate an aggregate of approximately 2,000 Mt of additional spent fuel each year. At this generation rate, the statutory limit of 63,000 Mt allocated for civilian spent nuclear fuel within the planned geologic repository will be reached by 2015 (**Error! Reference source not found.**). Industry experts have examined the possibility of expanding the first repository to accommodate the spent fuel generated by the continued operation of the nation's nuclear power plants through the middle of the century. However, without legislative change, the statutory capacity of the selected site at Yucca Mountain, Nevada, will eventually be exceeded. Since the majority of existing nuclear power plants are expected to remain operational until 2030 and beyond, the quantity of spent fuel produced presents a challenge both to existing plants and to building new nuclear power plants.

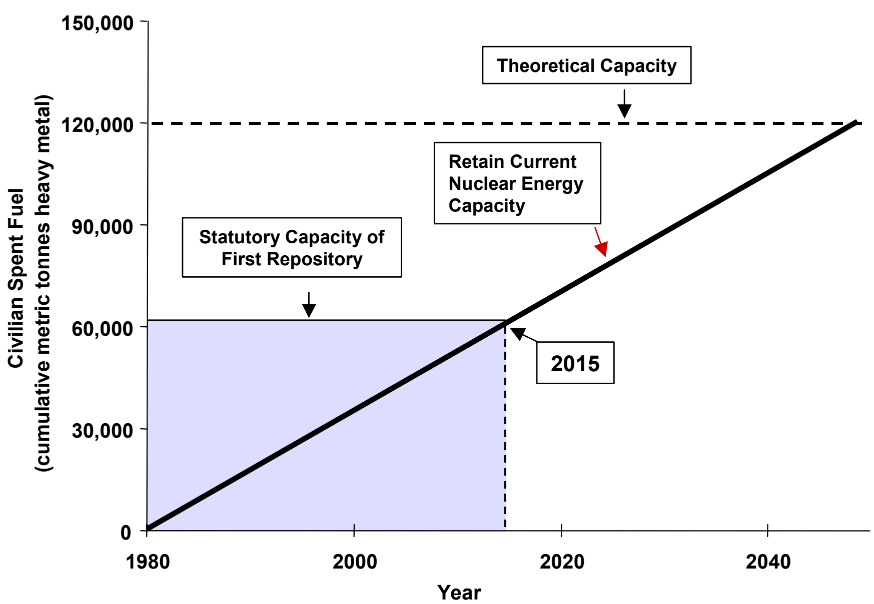

Figure 3-1. Spent Fuel Waste Accumulation vs. Time

In addition to the waste disposal issue, the nation must also be concerned with proliferation risks. While the handling of highly radioactive spent fuel in the short term is dangerous and expensive, decay of the fission products over time could allow access to and retrieval of the plutonium after 50 to 100 years. Figure 3-2 shows that hundreds of metric tons of plutonium have already accumulated in commercial spent fuel in the U.S. alone. The U.S. has become increasingly concerned about the global accumulation of plutonium, which presents an important proliferation risk worldwide. While spent fuel in the U.S. does not present a proliferation risk, only a third of the world's nuclear power plants are in the U.S. Developing economical technologies to address this long-term threat is in the interest of the nation's security.

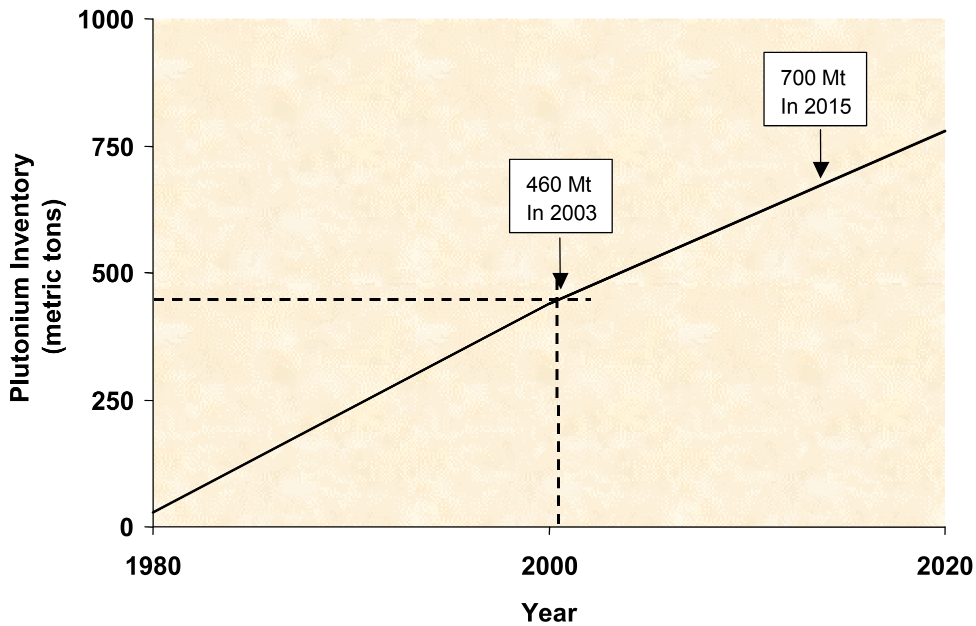

Figure 3-2. Plutonium Inventory in U.S. Commercial Spent Fuel

There are treatment technologies used around the world today that can reduce the volume of high-level waste; however, they engender significant proliferation concerns that limit their widespread application. Therefore, new treatment technologies should be innately proliferation-resistant and achieve the technical goals while avoiding problems that have restricted the use of spent fuel treatment technologies in the past. Further, to enable the U.S. to consume the large inventory of fissile plutonium from commercial spent nuclear fuel in a more proliferation-resistant manner, it will be necessary to develop advanced nuclear fuels that can be used in today's commercial nuclear power plants.

Finally, improved use of energy resources, such as the plutonium and uranium in spent fuel, is an important element of a sustainable nuclear energy strategy. If the Secretary of Energy's Nuclear Power 2010 Initiative is successful, the U.S. will start building new nuclear plants within the next ten years that will operate until at least 2070. As a result, research into technologies to make the most efficient use of nuclear fuel resources will support long-term energy independence. Moreover, the spent nuclear fuel currently stored at nuclear power plant sites contains the energy equivalent of <u>two full years</u> of the nation's oil imports and can be returned to the nation's energy supply through the technologies developed by AFCI.

In summary, the country faces a situation in which nuclear waste disposal issues linger, proliferation is a concern, and valuable energy resources are not being utilized. The question the nation faces is, "Should the U.S. treat and recycle spent nuclear fuel?"

In answering this question, it is important to recognize that even with the most ambitious goals for AFCI research, future spent fuel treatment and transmutation technologies will not obviate the need for a geologic repository. Nuclear Energy (NE) and Office of Civilian Radioactive Waste Management (OCRWM) need to work together to achieve objectives in the national interest. For instance, in the long term, it may be possible to apply advanced nuclear technologies to reduce both the cost and difficulty of operating a geologic repository, and reduce the technical need to build multiple repositories in the future. Doing so could help reduce one of the main long-term barriers to the expanded use of nuclear energy. In addition to these benefits, AFCI may someday enable the nation to reduce the toxicity of spent fuel placed in the first geologic repository. By destroying the most toxic, long-lived radioactive components of the spent fuel, it may be possible to significantly reduce the time it takes for the toxicity in commercial nuclear waste in a repository to decay to the toxicity of natural uranium ore. Again, while a deep geologic repository is still required, AFCI technology can optimize its technical performance and reduce the cost.

The AFCI program and related efforts by other countries are focused on finding the most effective technologies to accomplish four basic steps in spent fuel treatment:

1) Reduce spent fuel volume by creating a final high-level waste form that is lower in volume than the original spent fuel.
2) Remove radioactive elements that dominate the decay heat in spent fuel in order to expand repository thermal capacity.
3) Separate long-lived, highly toxic elements (i.e., higher actinides such as plutonium and americium) that present the most difficult disposition challenges.
4) Reclaim spent fuel's valuable energy by providing technologies to recycle highly toxic spent fuel elements in reactors or accelerator-driven systems, while providing for their destruction.

Accomplishing these steps requires the use of complex chemical and nuclear reaction processes that can be conducted in a manner that is safe, cost effective, environmentally friendly, and proliferation-resistant. The AFCI program is structured to develop and demonstrate feasible and desirable options for spent fuel treatment and transmutation and this plan delineates the R&D required to further develop these technologies.

Spent fuel treatment alternatives have been identified through preliminary screening analyses. The attributes of these alternatives are many, and trade-offs must be considered in an integrated manner. For example, France and the United Kingdom are already separating and recycling plutonium using the Plutonium Extraction process (PUREX). This approach addresses the energy advantage of recycling fissile material, but it suffers from the fact that pure plutonium is a product of this process and waste disposal costs are not necessarily reduced. AFCI is not contemplating this process. Instead, the AFCI strategy is to develop a separations process that does not extract pure plutonium. In this case, more proliferation-resistant plutonium mixtures are maintained throughout all separations steps and the mixtures are subsequently used to manufacture reactor fuel. This allows the fissile material to be used, reducing plutonium inventory and dramatically reducing repository costs. Alternatives such as Advanced Uranium Extraction process (UREX+), a solvent extraction process that enables the partitioning of spent fuel into components that facilitate enhanced waste management; pyrochemical oxidation (PYROX); hybrids; and advanced aqueous processes have the potential of fulfilling these objectives. These processes enable a fuel cycle that reduces plutonium inventories, recovers uranium for future use, decreases the short-term heat load, and reduces the disposal costs for the repository.

The Accelerated Transmutation of Waste (ATW) program, originally funded by Congress in FY00, and its successor, the Advanced Accelerator Applications (AAA) program, have investigated the feasibility of accelerator-driven systems to transmute long-lived toxic components of nuclear fuel. The AFCI program combines the technology development in these programs with fuel development and separation technologies to address the entire fuel cycle.

In 2002, the program demonstrated (at the Savannah River Technology Center) separations technologies that extracted uranium at high purity from spent nuclear fuel, resulting in material that has the characteristics of Class C (low-level) waste. Since uranium constitutes more than 95% of spent nuclear fuel mass, this could be an important waste management technique. There is a potential benefit to the repository as it opens the possibility to use less costly containers for the reprocessed high-level waste material than would be required if completely spent fuel assemblies were to be disposed. The program has recently demonstrated removal and separate management of cesium and strontium at Idaho National Engineering and Environmental Laboratory (INEEL) to significantly decrease the short-term heat load in the repository, permitting higher density storage of the remaining high-level waste. The next step is to evaluate processes to remove the minor actinides to decrease the long-term radiotoxicity and heat load. Collectively, these effects could result in substantial decreases in the number of waste packages that must be stored in the repository.

Other recent accomplishments include:

- Fabricated and commenced irradiation of non-fertile and low-fertile metallic fuel samples containing plutonium, neptunium and americium.
- Fabricated and prepared for irradiation higher actinide bearing nitride and oxide test fuels.
- Built a lead-bismuth test loop and completed 1000 hour corrosion test.

Parallel with these efforts, more proliferation-resistant fuel using recycled plutonium is being developed and demonstrated, which will slow the growth of the U.S. civilian inventories of plutonium. Because the current fleet of reactors is expected to operate for many more years, it is economically advantageous to use these reactors. As a result, one of the fuel forms resulting from this program could be used in the current LWR fleet and ALWR or HTGR. To achieve a fully closed fuel cycle, fast neutron spectrum reactor systems will be required. Accelerator-driven systems (ADSs) may also be needed to transmute problematic actinides. Such systems will be designed to transmute and effectively extract the energy from actinides thereby reducing both the long-term radiotoxicity and heat load on the repository. To support this objective, the program is advancing the knowledge base for transmutation engineering by measuring critical physics and materials properties.

More recently, there have been several changes in program direction:

- Shift from early implementation of technologies to focused R&D to inform the Secretarial recommendation in 2007-2010 on need for a second repository.
- Defer indefinitely design and construction of large scale Spent Fuel Treatment Facility.
- Reduce scope of UREX+ engineering-scale demonstration.
- Investigate other advanced aqueous processes.
- More emphasis on systems analysis including modeling.

Upon the successful completion of AFCI research, development, and scaled demonstrations, it is envisioned that sometime after 2020, the industry would be able to implement the separations technology in a commercial facility. In such a facility, the full gamut of extraction and partitioning processes would be conducted. Fabrication of proliferation-resistant fuel in a commercial facility would follow the start-up of the separations facility and commercial reactors would use this fuel.

In summary, AFCI technologies will increase national security by reducing inventories of commercially generated plutonium, enhance energy independence by recovering the energy value contained in spent nuclear fuel, and dramatically reduce disposal costs for nuclear waste.

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4.0 AFCI TECHNICAL APPROACH AND PROGRAM INTERFACES

4.1 Integrated Program

The AFCI program is being executed in an integrated manner with the Gen IV program. (See Section 6 for further information.). AFCI will develop reactor fuels and supporting fuel cycle technologies for both the transitional and advanced fuel cycle for Gen IV reactors. Integration of these efforts enhances cost effectiveness and maximizes the use of unique facilities.

Gen IV fuel development, as part of the AFCI program, is driven by the reactor requirements specified by the Generation IV Systems Integration Managers. A separate plan, the *Advanced Gas Reactor Fuel Development and Qualification Program Plan*, has been written for the NGNP and is not included here. Fuel development plans for the other Gen IV systems are still in the formulation stage.

AFCI is responsible for providing an effective transition strategy to address the legacy of the current open fuel cycle. The technologies needed to enable the transition from the open fuel cycle are primarily focused on technical issues associated with treating LWR and ALWR spent nuclear fuel, such as reducing the volume and heat generation (short-term) of material requiring geologic disposal. These issues are being addressed through the development and demonstration of advanced separations technologies and proliferation-resistant recycle fuels. The recycled fuels would then be used in existing and ALWRs and possibly gas-cooled reactors. This approach provides technical options that could be used to optimize use of the nation’s first repository and potentially delay or eliminate the need for an additional repository. Research activities include developing proliferation-resistant separations processes and fuels to recover the energy value of the materials while destroying significant quantities of plutonium in LWRs.

The advanced fuel cycle efforts of the AFCI are also addressing the fuel cycle options required for Gen IV reactors. This part of the program will develop fuel cycle technologies to destroy minor actinides in fast neutron spectrum systems, greatly reducing the long-term radiotoxicity and heat load of high-level waste sent to a geologic repository. This will be accomplished through the development of a transmutation fuel cycle using Gen IV fast reactors and possibly ADS.

Work completed by the AFCI (and its predecessors) and Gen IV has enabled DOE to clearly identify the objectives and approaches for research that will enable DOE, Congress, and industry to make informed decisions about the potential of advanced fuel cycle technologies. The technical approach is to use these objectives as the drivers for creating technically feasible options for managing high-level nuclear waste for both the transitional phases (Phases 1 and 2 from Figure 2-2) and for the longer-term Gen IV fuel cycle (Phases 3 and 4).

The **AFCI Transitional Fuel Cycle R&D** addresses specific near- to intermediate-term issues facing nuclear power: Objectives of this work are to develop and demonstrate technologies that have the potential to

- Reduce high-level waste volumes,
- Increase the capacity of the planned geologic repository,
- Reduce the technical need for a second repository,
- Reduce long-term inventories of plutonium in spent fuel, and

- Enable recovery of the energy contained in spent fuel.

The **AFCI Gen IV Fuel Cycle RD&D** supplements the transitional AFCI objectives and addresses the following objectives:

- Reduce the toxicity of spent nuclear fuel,
- Reduce the long-term heat generation of spent nuclear fuel,
- Provide a sustainable fuel source for nuclear energy, and
- Support the future operation of Gen IV nuclear energy systems.

Longer-term technology activities are focused on developing and demonstrating fuels, treatment processes and transmutation technologies to provide support for Gen IV. During program plan period, Gen IV will complete the viability stage for all concepts, including fast reactor concepts. Therefore, the AFCI long-term activities provide fuel cycle assessments for the different fast reactor concepts of Gen IV and help guide final selection of the reactor system(s) to be deployed. This work is closely coupled to the Gen IV implementation schedule. A preliminary decision will be made by 2010 as to which Gen IV fast reactor system(s) will be pursued for development and demonstration.

One element of the longer-term work is focused on ADS. Many countries are considering ADS as a viable approach to transmutation because such systems may be capable of destroying long-lived radioactive isotopes without producing plutonium. By 2010, a preliminary determination will be made concerning the need for combining a Gen IV fast reactor and an ADS as a means of enhancing the transmutation capability.

4.1.1 Program Elements and Major Milestones

The AFCI technical program is organized by elements spanning all activities necessary to support Gen IV fuels, the transitional fuel cycle, and the Gen IV advanced fuel cycle. Details of these elements are provided in Section 5 of this plan. The four major program elements are:

1) **Separations**. AFCI separations development focuses on separations and waste management technologies that would support the transitional fuel cycle as well as Gen IV systems. This program element consists of process design and demonstration via laboratory-scale and engineering-scale testing.
2) **Fuels.** AFCI fuels development includes the NGNP and Gen IV fuels, proliferation-resistant LWR/ALWR fuels, and prototypic transmutation fuels for Gen IV reactors. Each activity includes research, development, testing, safety, and NRC licensing support, as well as demonstration activities to enable the design and construction of proliferation-resistant fuel fabrication facilities.
3) **Transmutation Science and Engineering.** Both Gen IV fast reactor and accelerator based transmutation research activities are included in this longer-term element. Transmutation activities focus on providing the engineering basis to support near-term program decisions and providing a path forward for implementation, primarily consisting of physics, materials, coolants, targets, and accelerator technology.
4) **Systems Analysis**. Systems analysis crosscuts the other technical areas and provides the models, tools, and analyses to assess the feasibility of design options and inform

key decision makers in the program. The systems analysis activity is conducted jointly with Gen IV and coordinated through the technical integration function of each program, as described in Section 6.1.

The program also includes important research activities at universities. University Programs can be considered a fifth element of the overall program. Efforts in this area support university research in areas of benefit to the program. This element also supports a fellowship program to encourage students to study nuclear engineering.

International collaboration is an important part of each program element. Collaboration allows the U.S. to leverage R&D investments and gain access to data and facilities not available in the U.S.

Each program element has a detailed technical plan that is discussed in Section 5. From these plans, major milestones have been identified as illustrated in Figure 4-1. These major milestones are a mechanism for tracking technical progress.

Successful completion of these milestones will allow the program to meet the key objectives.

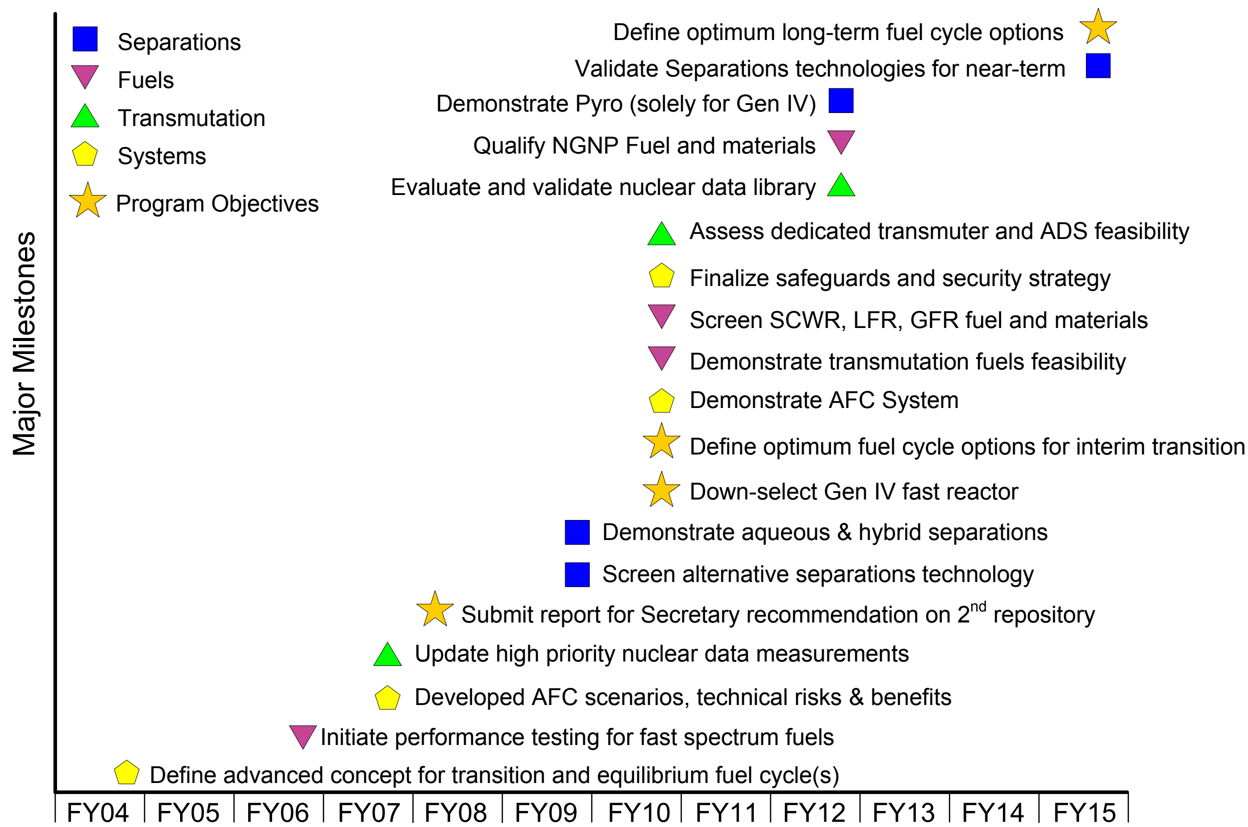

Figure 4-1. AFCI Program Major Milestones

Another major challenge in a complex research and development program such as AFCI is performing consistent assessments of the relative maturity of the various technology elements within the program. Such assessments are essential to measuring technical progress, guiding investment decisions, and ensuring that technologies are developed to an appropriate level to support key program milestones, such as technology selections and technology deployments. Within AFCI, Technology Readiness Levels (TRLs) are employed to assess technology maturity. DOE, NASA, and DOD have employed TRLs in a variety of forms for many years. TRLs provide a systematic measurement system that support assessments of the maturity of a particular technology and the consistent comparison of the maturity between different types of technology.

5.0 AFCI TECHNICAL PROGRAM ELEMENTS

AFCI is organized by program elements (Separations, Fuels, Transmutation Science and Engineering, Systems Analysis, and University Programs). Each technical program element is described in the following sections with respect to its associated goals and objectives, major activities to achieve the goals and objectives, approximate timeframes for performing activities to attain the overall AFCI mission, and major milestones to be accomplished over the next ten years.

5.1 Separations

5.1.1 Separations Program Element Overview

The AFCI program provides an alternative strategy for management of spent nuclear fuel which will, through separations and transmutation, reduce the cost and hazards of repository disposal, reduce the amount of civilian plutonium accumulating in the nuclear fuel cycle, and recover unused fuel and its energy value from the waste. The separations program element contributes to the achievement of the AFCI mission by making it possible to eliminate those radionuclides that most strongly impact repository performance, while at the same time decreasing the quantities of material requiring disposal as high-level waste.

Because of its environmental advantages and abundant fuel resource base, nuclear power is expected to be an important source of energy in the U.S. in the future. Projections for the growth of nuclear power in the U.S. vary widely, with generating capacity between 175 and 500 GWe in 2050 (about 100 GWe today).[1] The legislated capacity of the Yucca Mountain geologic repository (70,000 tons) will be reached in 2015 as the spent fuel inventory grows from the operation of the current fleet of commercial power reactors. The various growth scenarios would require disposal capacity of 2.4–4.3 times the legislated capacity of Yucca Mountain by 2050 if the U.S. continues using the once-through LWR fuel cycle. Lacking legislative relief, the difficult and costly process of siting, licensing, and constructing a geologic repository for high-level nuclear waste in the U.S. would be repeated a number of times over the next 40–50 years. Even if the repository capacity is increased by further exploration, the once-through fuel cycle would require at least one additional repository within three or four decades.

AFCI is intended to provide an alternative approach to high-level nuclear waste disposal in the future, by providing a closed fuel cycle technology that can support the current fleet of commercial power reactors as well as future reactors. Chemical separations technology development is an important part of this program, and the development effort is directed toward separations processes that facilitate the removal of those constituents of spent fuel that contribute most to the heat load and waste volume imposed on the disposal of high-level waste in the repository. Processes are being developed that will: (1) remove over 90% of the uranium in sufficiently pure form that it can be disposed as a low-level waste or re-enriched for recycle to LWRs; (2) remove over 99% of the cesium and strontium present in spent fuel, thereby greatly reducing the short-term heat load; and (3) separate the transuranic elements (plutonium, neptunium, americium and curium) for storage or for recycle to LWRs or future advanced reactors for fissioning, thereby greatly reducing the long-term heat load. It is estimated that the

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[1] EIA projection and MIT report.

capacity of the Yucca Mountain repository could be increased, in terms of equivalent tons of spent nuclear fuel, by a factor of 40-60 times by such processing. This would ensure the sustainability of an expanded nuclear energy supply system in the U.S. and delay the need for a second repository until well into the next century.

Both advanced aqueous and pyrochemical processing methods are being developed under the scope of AFCI. One aqueous process, known as UREX+, is at an advanced stage of technological maturity and could conceivably be deployed in the 2020–2025 time period. It represents a minor but significant departure from the processes presently utilized in commercial reprocessing plants in France and the United Kingdom. The pyrochemical processing methods are directed principally toward the treatment of spent fuels arising from the operation of third and fourth generation reactor plants, and the development benefits greatly from the experience gained in processing spent fuel from the EBR-II fast reactor.

Projections of the long-range future of nuclear power in the U.S. are complicated by the existence of many unquantifiable variables. They range from a nuclear phase-out to no growth through 2025 to sustained growth to 300–500 GWe by 2050. It is likely that LWRs and ALWRs will comprise the bulk of the U.S. nuclear generating capacity for at least another 50 years. Separations for the purpose of waste management will be important until it becomes practical to recycle separated plutonium (and perhaps neptunium) as mixed oxide fuel in thermal spectrum reactors. Subsequently, it may be possible to reduce the long-term heat load imposed on the repository by burning separated minor actinides (americium and curium) in dedicated fast-spectrum burner reactors. Finally, a transition to Gen IV reactor systems will occur, with full closure of the nuclear fuel cycle. These distinct periods in the evolution of the U.S. advanced fuel cycle strategy can be categorized as a series of phases (see Section 2.2). Phase 0 is the current once-through cycle with deployed commercial LWRs. Phase 1 is a transitional waste management phase in which commercial spent fuel would be processed to facilitate the disposal of high-level nuclear wastes in a manner that extends the effective capacity of the geologic repository. Phase 2 would see the recycle of fissile materials in ALWRs as mixed oxide fuel. Phase 3 involves the use of dedicated fast-spectrum burner reactors to destroy the minor actinide elements, Am and Cm, for reducing the long-term heat load on the repository. Phase 4 represents the transition to advanced Gen IV reactors with closed fuel cycles. An illustration of this strategy is shown in Figure 5-1. The timeframes shown in Figure 5-1 are only approximate and duration of the phase, or the intent of their overlap, are subject to change. This strategy offers a great deal of flexibility and offramp options as the nuclear energy future unfolds.

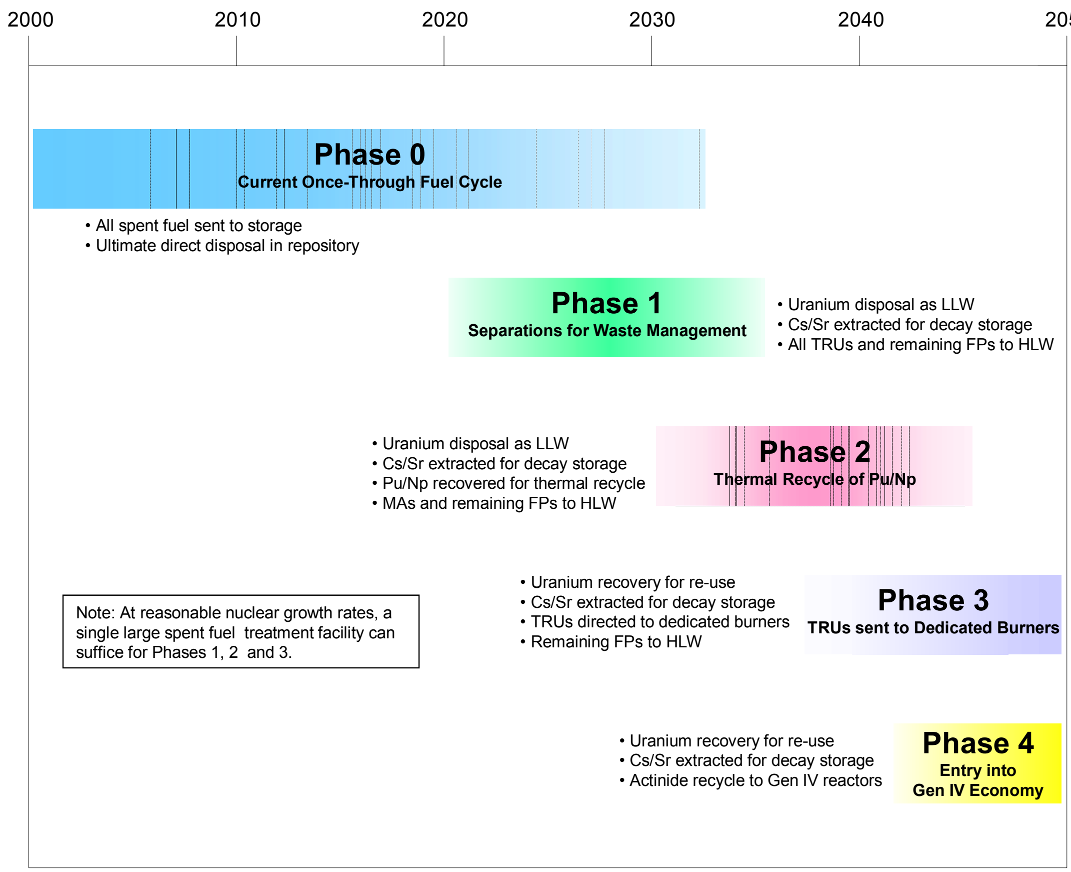

Figure 5-1. Phased strategy for the Implementation of Advanced Nuclear Fuel Cycles in the U.S.
Times are only approximate and durations of the phases or the extent of their overlap are subject to change.

Advanced Aqueous Processing

Aqueous reprocessing of LWR spent fuel is currently practiced in France, the United Kingdom, and Russia. Japan will soon begin operation of a commercial facility, the Rokkasho Reprocessing Plant. The scale of these processing plants is on the order of what would be required to accommodate the current rate of generation of spent LWR fuel in the U.S. (2000 Mt/yr), and the technologies employed are technologically mature. These factors were instrumental in selecting advanced aqueous processing as the reference method for development as part of the AFCI. Aqueous processing also affords the flexibility in process configuration required by the multi-phase strategy: the same plant that is used for Phase 1 can be easily reconfigured to support Phases 2, 3 and possibly 4.

Development of advanced aqueous processing methods for the treatment of spent LWR fuel is proceeding on schedule, and flowsheets for Phases 1-3 would be selected by the end of FY 2008. Process development is being guided by the preliminary separations criteria shown in Table 5-1.

Table 5-1. Preliminary Separations Criteria for Use in Process Evaluation and Selection

Criterion	Thermal Recycle, Fertile Fuel	Fast Reactor Recycle of U and All TRUs
Recovery Efficiency		
U	90%	90%
Pu/Np	99%	99%
Am/Cm	99.5%	99.5%
Cs/Sr	97%	97%
Tc, I	95%	95%
Purification Requirements		
U	99.9%, 99.97%*	99%
Pu/Np	99.5%	97%
Am/Cm	TBD	97%
Cs/Sr	<100 nCi TRU/g **	<100 nCi TRU/g **

*Higher purity requirement is for the option of re-enrichment of the uranium stream
**Purification as necessary to meet 10CFR61.55 requirements for Class C waste

Phase 1 Separations. The Phase 1 strategy is based on spent fuel processing for waste management purposes. Therefore, the process requirements are for separation of pure uranium (which could be disposed as low-level waste), extraction of cesium (and strontium in pure form (for decay storage and eventual disposal as low-level waste), efficient recovery of technetium and iodine (for incorporation into durable waste forms), and recovery of transuranic elements together with lanthanide fission products for repository disposal as a self-protecting waste form. Because the transuranic (TRU) waste is a long-term decay heat generator, consideration is being given to storage of this material in retrievable form so that it could be recovered before repository ventilation is terminated and further processed to recover the transuranics for recycle as fuel for future fast spectrum reactors. A schematic flow diagram for Phase 1 processing is shown in Figure 5-2. After conventional dissolution of the spent fuel in nitric acid, the clarified dissolver solution is sent to a solvent extraction process called UREX. The UREX process uses tri-butyl phosphate (TBP) as the extractant, with acetohydroxamic acid added in the scrub stage to reduce plutonium to the unextractable Pu(III) state. Uranium and technetium are co-extracted, and the technetium is then stripped at high acidity to yield a pure uranium stream and a pure technetium stream. The transuranics and the remaining fission products are in the UREX raffinate, which is then directed to the Cs/Sr extraction step. The present reference process for recovery of cesium and strontium is the CCD/PEG process (chlorinated cobalt dicarbollide/polyethylene glycol); the use of alternate extractants such as calixarenes is also being studied. After removal of the cesium and strontium, the raffinate is denitrated to produce a mixture of transuranic oxides and fission product oxides. Alternatively, the raffinate could be processed by the aqueous solvent extraction process for TRU recovery (TRUEX) to recover the transuranics together with the lanthanide fission products, with the remaining fission products going to the waste stream. In either case, the transuranics and accompanying fission products would be encapsulated and stored in the repository. The nature of the storage form is yet to be decided. It could take the form of a cermet fuel rod, utilizing part of the zircaloy cladding hull stream to provide the matrix material for eventual retrieval and use as a fuel or target in a fast reactor. The TRU product could also be encapsulated directly, with the proviso that further processing would be necessary before the fissionable material would be recycled. Regardless of the path taken, the Phase 1 processing scheme appears to have significant benefit to repository operation. The effective increases in repository capacity if all LWR spent fuel were to be processed before waste emplacement could be as much as a factor of 60.

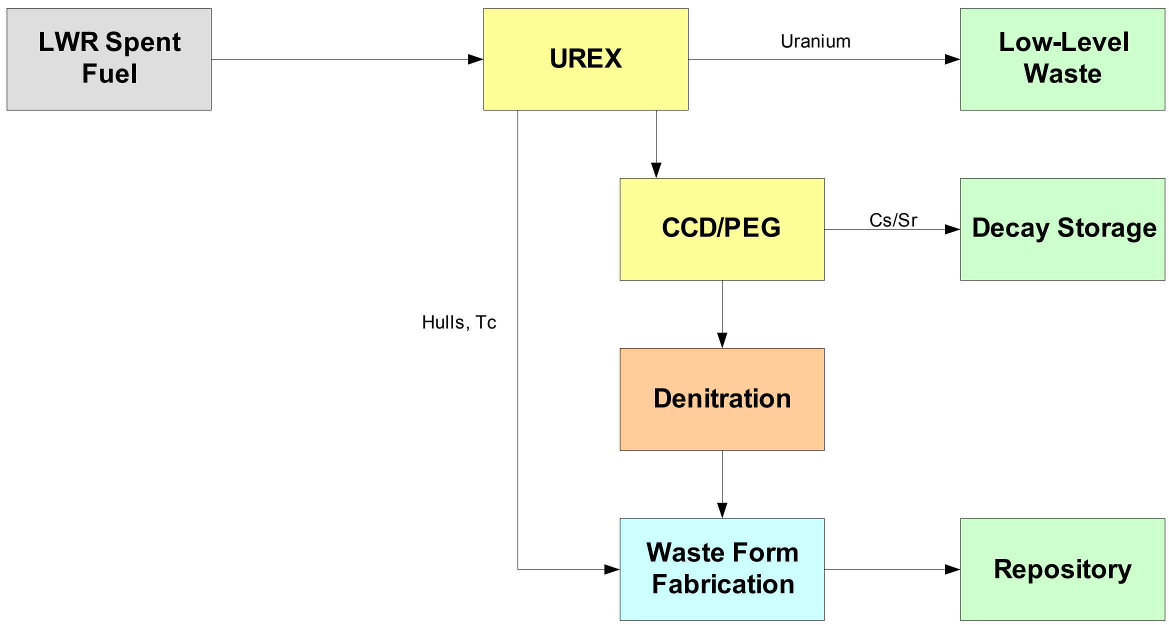

Figure 5-2. Phase 1 Processing of LWR Spent Fuel
Iodine recovery is not shown for purposes of simplification.

The AFCI program has demonstrated the elements of the Phase 1 process flowsheet at laboratory-scale at Westinghouse Savannah River Company (WSRC) and INEEL, with actual spent LWR fuel using the CCD/PEG process for cesium and strontium extraction. All process criteria were satisfied, in most cases exceeded by a wide margin. An engineering-scale demonstration is planned for the near future.

Phase 2 Separations. Phase 2 adds the extraction of plutonium (and perhaps neptunium) for recycle to thermal reactors. At least 30 of the existing 103 commercial nuclear power plants in the U.S. are capable of burning mixed-oxide fuel, and a transition period is anticipated over which time the recycled fuel could be qualified and incentives established for utilities to accept such fuel. Modification of the Phase 1 separations processes to achieve Pu/Np extraction are rather simple, with one possibility shown in Figure 5-3. Here, a TBP-based extraction step would be performed after the Cs/Sr extraction step. An alternative to this process is a co-decontamination process, in which the initial separation would be of (1) uranium, (2) technetium, and (3) plutonium/neptunium. The subsequent extraction of Cs/Sr could be with either the CCD/PEG process or an alternative such as a calixarene-based process. Once again, the AFCI program has successfully demonstrated all elements of both process options at laboratory scale at Argonne National Laboratory (ANL) and Oak Ridge National Laboratory (ORNL).

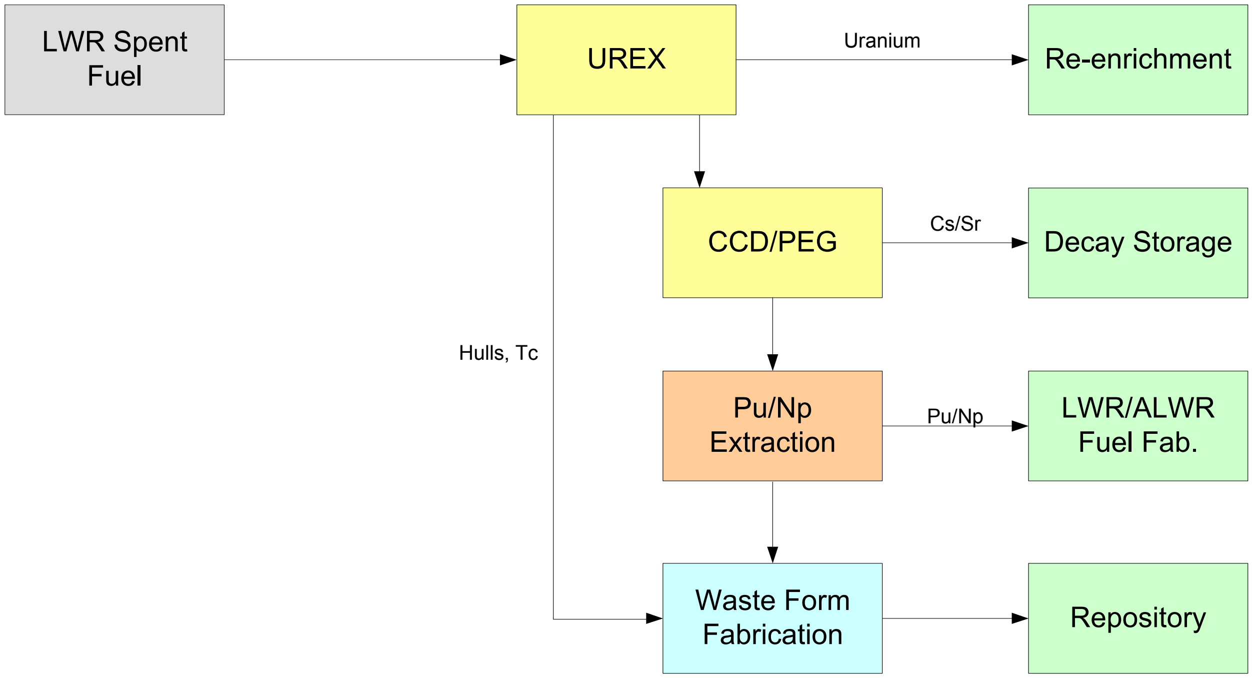

Figure 5-3. Phase 2 Processing of LWR Spent Fuel
Iodine recovery is not shown for purposes of simplification.

The minor actinides remaining in the waste stream are thought to be incorporated in temporary storage forms, as is the case in Phase 1. Given the possibility that storage of these materials may become permanent, it is most likely that the choice of encapsulation method will tend toward the more durable form.

Phase 3 Separations. In Phase 3 of the advanced fuel cycle, minor actinides are recovered for burning in fast spectrum reactor systems. The schematic flow diagram for this phase is shown in Figure 5-4. In this case, considerable development work remains to optimize the process for separation of the americium and curium from fission products, especially the +3 lanthanides that are difficult to separate from the +3 minor actinides. An extensive testing program is underway in both the U.S. and Europe, with the aim of developing the best process for Am/Cm separation. Two-step processes (separation of Am/Cm/lanthanides from the balance of the fission products, followed by separation of Am/Cm from the lanthanides) and one-step processes are being evaluated. The DIAMEX-SANEX process has been tested with some success in various laboratories, and recent spent fuel tests of the CYANEX-301® process have yielded excellent results.

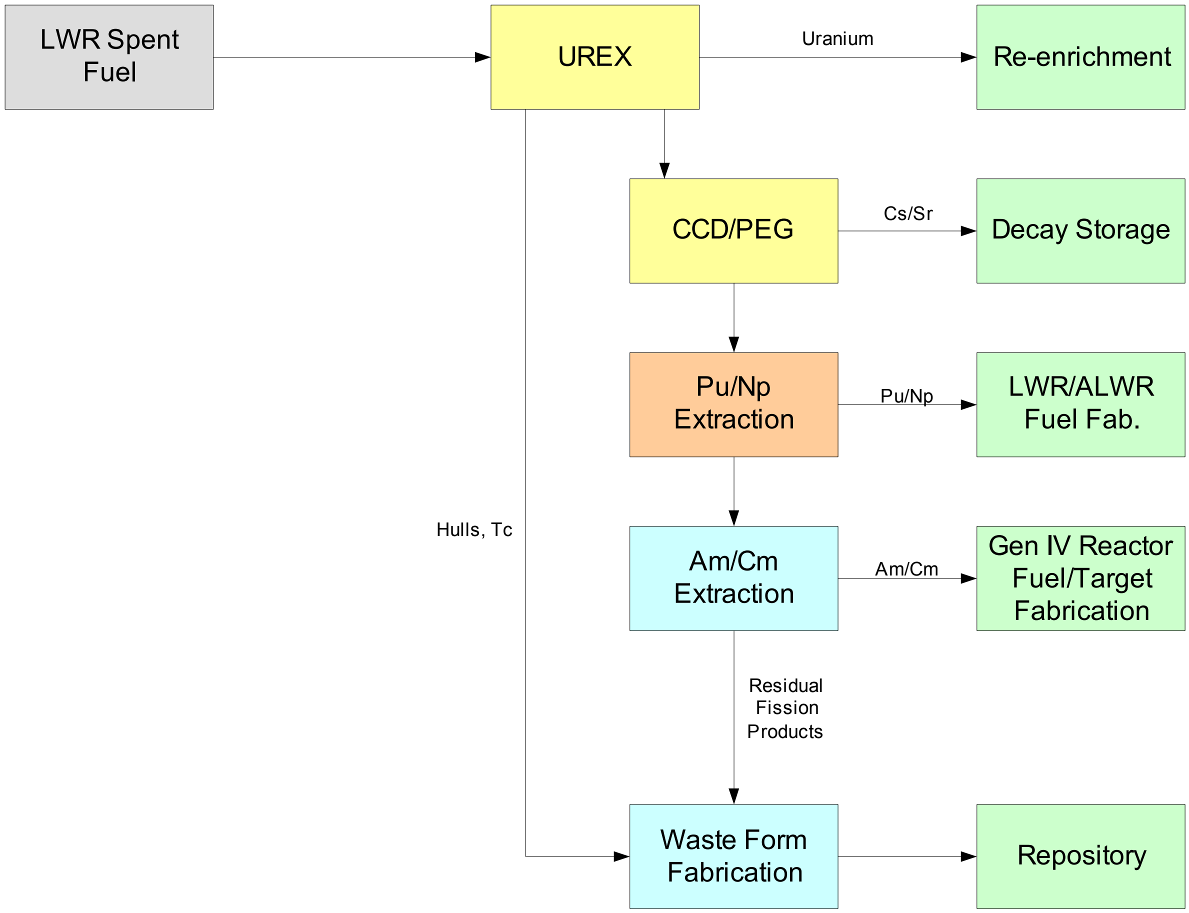

Figure 5-4. Phase 3 Processing of LWR Spent Fuel
Iodine recovery is not shown for purposes of simplification.

The residual fission products from Phase 3 processing would be placed in a ceramic waste form for repository disposal. Because the remaining fission products are comparatively benign (the only significant heat generator is Eu-154, with a half-life of 8.6 years), the fission product loading of this waste form can be quite high, leading to a very small volume of high-level waste for disposal.

Pyrochemical Processing

Fuel systems for Gen IV reactors, with the possible exception of the Supercritical Water Reactor, represent a significant departure from the commercial LWR oxide fuel. Many of the fuel types that are foreseen for these reactors are intuitively not compatible with aqueous processing of the sort discussed above, and include coated-particle fuels, inert matrix fuels (ceramic-ceramic and ceramic-metal), metal alloy fuels, mixed nitride fuels (e.g., AnN/ZrN, where An is actinide), and carbide fuels. Therefore, Phase 4 separations processes must consider the application of processing technologies besides aqueous. The general class of pyrochemical processes offers some distinct advantages in treating the variety of Gen IV fuels.

Electrorefining has been used for over four years to condition spent fuel from the EBR-II reactor. In this process, the irradiated metallic fuel is chopped and anodically dissolved in molten LiCl-KCl salt. Uranium is electrotransported to a metallic cathode, and the transuranics are left in the salt together with the active metal fission products for eventual incorporation in a ceramic waste form. Noble metal fission products (including Tc) are melted together with stainless steel cladding hulls to produce a metallic waste form. The addition of a transuranic recovery step to this process would make it applicable to the Phase 4 metallic and nitride fuels processing. Tests of TRU recovery methods are currently in progress in the U.S. and elsewhere. Addition of an electrochemical reduction head-end step would make the process applicable to both dispersion and inert matrix oxide fuels.

To date, development of pyrochemical processing technologies have been limited to work on metal alloy and nitride fuels for fast reactors. Process concept development for the pyrochemical processing of coated-particle fuels is now underway, and work with carbide fuel will begin soon. The conduct of extensive experimental programs, other than those involving the conditioning of EBR-II fuel are being deferred until the Gen IV fuel types are better defined.

5.1.2 Separations Goals and Objectives

The goal of the separations technology element of the AFCI is to develop chemical partitioning processes that can be applied economically, and with the required level of proliferation resistance and physical protection, to the treatment of spent nuclear fuels arising from the operation of current-generation nuclear power plants and from advanced nuclear power systems of the future. Initially, these processes will be utilized in a waste management role (Phase 1), with the intention to reduce the impact of high-level waste disposal on the operation of the Yucca Mountain geologic repository by reducing the short-term heat load and volume of waste disposal. Subsequently, the partitioning processes will eliminate the long-term heat load and radiotoxicity of nuclear wastes by separating the transuranic elements for destruction by fissioning in available reactor systems (Phases 2 and 3). Ultimately, fuel cycle separations technologies will be applied to closure of the of advanced Gen IV reactors (Phase 4).

5.1.3 Separations Major Milestones

Major milestones of Separations Technology are shown in Figure 5-5.

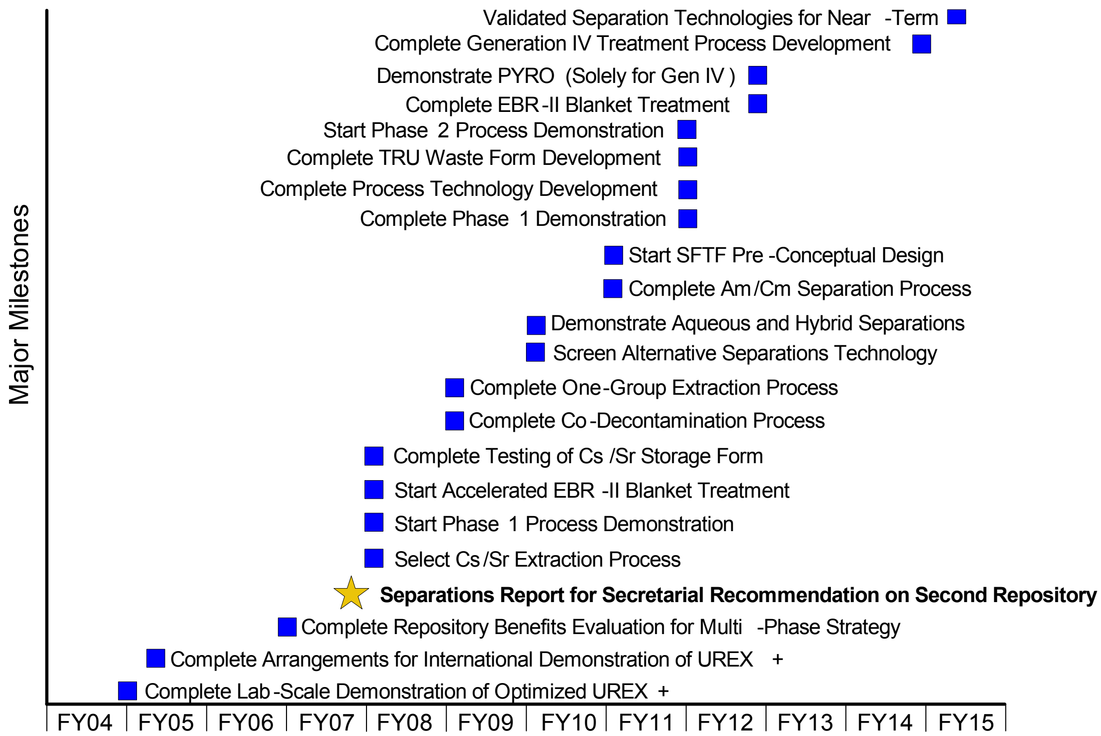

Figure 5-5. Separations Technology Development Major Milestones

Elements of the Separations Technology Development Activity

Advanced Aqueous Separations. This program element entails the development of advanced aqueous processes for the partitioning of spent nuclear fuels. The processes involved relate to the highly successful process used in current commercial practices in several countries, with added steps that permit the detailed partitioning required for employment in an advanced fuel cycle that is directed toward improved management of nuclear wastes. The development effort focuses on the UREX+ process. The process begins with the dissolution of spent fuel in nitric acid. Radioiodine is recovered from the dissolver tank, and the clarified dissolver solution is sent to the first solvent extraction cycle, where uranium and technetium are extracted as separate streams. This step has been successfully demonstrated at small scale with actual spent fuel. The waste stream from the first cycle is then directed to a cesium/strontium extraction process, for which there are a number of candidate processes. One of these, the CCD/PEG process, has also been demonstrated at laboratory scale. After removal of the cesium and strontium (which removes the major short-lived heat-generating radionuclides), the waste stream is sent to a process step that removes plutonium and neptunium for potential recycle to thermal reactors. Next, the remaining solution is directed to a minor actinide removal step. The process used for minor actinide (americium and curium, principally) removal is under development in Europe because these elements are responsible for the long-term heat load and the bulk of the remaining radiotoxicity of high-level nuclear wastes. This extraction is among the most difficult because the valence state of americium and curium is difficult to change and the minor actinides tend to extract with the lanthanide (rare earth) fission products. A number of candidate processes are under investigation. Both one- and two-step processes appear viable, with our goal to develop one that is both efficient and economical. After this final extraction step, the remaining waste stream is free of actinides, cesium, and strontium; and the fission product content is rather benign and conducive to compact storage in simple repository containers.

A number of variants of the reference process described above are under study, with the intention of establishing a process that meets the needs of the waste management and nuclear power systems in the U.S. As described before, the Phase 1 process may be limited to a group extraction of the transuranic elements, with no concern for lanthanide separation. This group extraction process must be developed and demonstrated at adequate scale. A co-decontamination process, which extracts uranium, plutonium and neptunium before extracting the cesium/strontium, may be more amenable to industrial-scale processing and is also the subject of study. A voloxidation head-end process is also under development, with the aim of facilitating the removal of volatile fission products and improving the decladding process. The plan is to complete the development and laboratory-scale demonstration of the UREX+ process and its variants by the end of FY 2008, whereupon a down-selection will be made and preparations made for a larger-scale process demonstration.

The development of advanced aqueous processing technologies benefits greatly from a collaborative arrangement with the Commissariat à l'Énergie Atomique (CEA, France). This collaboration has expanded significantly in the past few years to include many of the advanced processes of interest to AFCI, and has included access to technologies developed by CEA for commercial applications. An initiative launched in 2003 by the Office of Civilian Radioactive Waste Management builds on the DOE-CEA collaboration and will possibly make the commercial facilities of COGEMA at their La Hague reprocessing plant in Normandy available for a large-scale demonstration (80 tons of PWR spent fuel) of the UREX+ process. This demonstration could be completed by the end of FY 2007 and will be supplemented by related cooperative experiments at the CEA facilities of the Marcoule Nuclear Center.

Pyrochemical Separations. This element involves the development of a hybrid aqueous/non-aqueous process that has the potential for reducing the size and complexity of spent nuclear fuel processing operations. The pyrochemical process steps would follow the normal aqueous solvent extraction process for removal of uranium and technetium, with the liquid waste stream (less uranium and technetium) then being calcined to produce a solid product consisting of transuranic and fission product oxides. This comparatively low-volume product would then be reduced to the metallic state, making it amenable to partitioning by electrochemical means. The process development effort includes the demonstration of the efficiency of oxide reduction; high efficiency is necessary to preclude the carryover into the extraction step of unreduced oxides, which could hinder the extraction process. Development of the hybrid process is planned for completion towards the end of FY 2009. This development also includes the demonstration of a pyrochemical process for cesium/strontium recovery.

Engineered Product Storage. The treatment of LWR spent fuel involves the generation of a number of product streams, including pure uranium oxide and the transuranic oxides, separated either as plutonium/neptunium and americium/curium or as one group. An additional product stream is the cesium/strontium pair. In Phase 1, the transuranics may be grouped together with fission products other than cesium and strontium. This storage form may be manifested, as a cermet product involving a dispersion of transuranic oxides in a metal matrix comprised of cladding hulls. In all cases, an optimum means for storage of these products is needed before their disposal or utilization. This element is directed toward the evaluation of various storage options, including the form of the product to be stored and the technical and economic feasibility of its preparation. The use of conventional dry storage casks, similar to those used presently for spent fuel storage, is being studied for storage of some of the products.

Spent Fuel Treatment Facility Scoping Design. This program element has the purpose of evaluating design concepts for a large spent fuel treatment facility that could be used for the process of LWR spent fuel as well as the spent fuel discharged from future advanced reactors. A primary benefit of these studies is in the selection of process flowsheets for optimum plant performance and in the identification of process improvements that can reduce the size and extent of process equipment required, thereby reducing plant costs. This program element involves a minimal effort until such time that it becomes necessary to initiate actual pre-conceptual design of a production-scale plant, currently projected to begin in FY 2011.

Gen IV Separations Development. This element involves the development of advanced processing methods for application to Gen IV fuel systems. Initial work will focus on fuels for the NGNP; studies will include pyrochemical processing methods such as electrochemical processing and halide volatility processing. The processes to treat all currently planned types of Gen IV fuels are to be completed by FY 2012, leading to a process demonstration in the 2014–2015 period as necessary.

Advanced Process Development. With the construction of a large spent fuel treatment facility well into the future, there is a need to evaluate and develop advanced processing concepts that could be implemented in a future plant. This program element is directed toward such development and includes the evaluation of advanced concepts that are presently notional or at laboratory scale. Concepts that are farther along, such as advanced dissolver designs, actinide crystallization processes, advanced electrochemical process equipment designs (electrorefiners and electrolyzers), membrane separators, supercritical fluid separations, and nanotechnologies, are under active investigation. Also included in this element is the design of other specialized process equipment including advanced centrifugal contactors and instrumentation for process control, monitoring and safeguarding. Completion of the development of these advanced process technologies is expected by the end of FY 2011.

EBR-II Spent Fuel Treatment. A significant quantity of spent fuel and blanket assemblies remains after the shutdown of the EBR-II reactor. These fuels are unique in that the metallic fuel and blanket slugs are sodium-bonded to the cladding tubes for heat transfer purposes. Accordingly, they require processing before disposal because regulations preclude the disposal of elemental sodium in the repository. The fuel rods are a particular problem because the sodium has infiltrated into the pores in the fuel material produced by fission gas agglomeration. The fission gases were eventually released as the pores became interconnected. A total of about 3 metric tons of driver fuel and 21 tons of blankets remain in the inventory. Treatment of these materials was initiated in 1999, using a conditioning process that involved anodic dissolution of the actinides and fission products in a molten salt electrolyte, with uranium recovered at the cathode of the electrorefining cell by a process of electrotransport. Plutonium and the minor actinides and active metal fission products remain in the electrolyte salt and are ultimately converted into a glass-ceramic composite waste form. The noble metal fission products remain largely in the anode basket and are combined with the cladding hulls to produce a metallic waste form. Work on processing and qualification of these waste forms will continue over the period of this plan, while means are sought to increase the throughput of the condition process. Two electrorefiners are installed in the Fuel Conditioning Facility hot cell at Argonne National Laboratory-West, one configured for driver fuel treatment and one for blanket conditioning. Presently, driver fuel can be treated at a rate of 135–150 kg per year; the blanket throughput has been about 500 kg per year. Driver fuel processing is limited by criticality concerns; the average discharge enrichment of the fuel is about 57%. The recovered uranium is down-blended to produce low-enriched uranium, and the product is currently being stored on-site. Means for increasing the rate of blanket processing are being developed. Three options are currently under study: (1) high-throughput electrorefining, using the technology developed under the Advanced Process Development program element; (2) sodium removal and slug canning; and (3) sodium removal followed by melting/dilution of the uranium with uranium from other sources, possibly including driver fuel, for the purpose of reducing plutonium content to acceptable levels. By the end of FY 2006, the preferred process for blanket treatment should be selected, with blanket processing to be completed by FY 2012 if funding support is sustained. This will greatly reduce the time and cost required to comply with the agreement to remove all spent fuel from the site by 2035. AFCI prepared a detailed plan on the treatment of EBR-II spent fuel in October 2003.[2]

Key Milestones

Important milestones for Separations Technology Development are as follows:

FY 2004

Advanced Aqueous Separations

- Complete a laboratory-scale hot demonstration of the optimized UREX+ process.
- Complete the analysis of sludge and hulls from UREX/UREX+ hot demonstration.
- Demonstrate the modified direct denitration process with Pu/Np solution.
- Demonstrate the reverse TALSPEAK process for Am/Cm separation.
- Optimize the Cs/Sr aqueous extraction process.
- Specify the Cs/Sr storage form and vehicle.

Advanced Process Development

- Complete the uranium crystallization tests in loop system
- Complete initial liquid cadmium cathode (LCC) recovery of TRU from EBR-II spent fuel.
- Develop the process concept for coated-particle fuel treatment.

EBR-II Spent Fuel Treatment

- Treat 135 kg of EBR-II driver fuel.
- Document EBR-II waste form qualification testing.

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[2] EBR-II Spent Fuel Treatment Report to Congress, October 2003, (available on DOE-NE website nuclear.gov).

FY 2005

- Select the reference UREX+ process flowsheet.
- Initiate TRU waste product form development.
- Demonstrate the one-group extraction process for transuranics.
- Demonstrate the advanced Cs/Sr extraction process.
- Conduct a laboratory-scale hot demonstration of co-decontamination process.
- Evaluate alternative extractants for minor actinides and their separation from lanthanides.
- Initiate the design of an alternative EBR-II blanket processing system.
- Develop a process concept for pyrochemical recovery of Cs and Sr.
- Complete arrangements for international demonstration of the UREX+ process.

FY 2006

- Demonstrate advanced pyrochemical TRU recovery process equipment.
- Complete the planar electrode electrorefiner design.
- Complete a repository benefits evaluation for multi-phase strategy.
- Select a preferred process for accelerated EBR-II blanket treatment.
- Define process technology development requirements for a large plant.
- Assess physical protection requirements for a large spent fuel treatment facility.

FY 2007

- Select a reference aqueous Cs/Sr extraction process.
- Complete an international demonstration of the UREX+ head-end process steps.
- Start the Phase 1 process demonstration in collaboration with CEA.
- Start the accelerated EBR-II blanket treatment.
- Complete testing of the reference Cs/Sr storage form.

FY 2008

- Complete development and testing of the one-group TRU extraction process.
- Complete development and testing of the co-decontamination process.
- Complete all UREX+ laboratory-scale development tests.
- Complete development of pyrochemical method for Cs/Sr extraction.

FY 2009

- Complete development and demonstration of the hybrid aqueous/pyrochemical separations process.
- Complete preparations for Phase 1 process demonstration.

- Complete screening of advanced separations technology concepts.

FY 2010

- Complete Am/Cm separations process development.
- Start pre-conceptual design of a large spent fuel treatment facility.
- Complete first stage of the collaborative separation demonstration with CEA.

FY 2011

- Complete the Phase 1 demonstration.
- Complete process technology development (equipment, instrumentation, procedures).
- Complete TRU waste form development and testing.
- Start the Phase 2 process demonstration.

FY 2012

- Complete accelerated EBR-II blanket treatment.
- Complete initial review of the spent fuel treatment facility pre-conceptual design.

FY 2013

- Complete preparations for the Phase 2 process demonstration.

FY 2014

- Complete the Gen IV spent fuel treatment process R&D phase.
- Start preparations for the Phase 3 process demonstration.

5.2 Fuels Development

The fuels development element is responsible for conducting R&D activities for fuel and clad materials to be used in advanced fuel cycles. R&D activities cover both current LWRs, the NGNP, and dedicated transmutation systems if needed.

5.2.1 Fuels Development Program Element Overview

The AFCI implementation strategy consists of multiple phases, which are equally important in achieving long-term program objectives. Figure 5-6 is a conceptual plot of nuclear waste generation (ω) versus nuclear energy generation (Q). Waste generation ω does not represent a single value but is a measure of multiple parameters referring to the waste volume, short-or long-term decay heat, the plutonium content, or the radiological risk. The transition to an ultimate closed fuel cycle using Gen IV reactors is to be achieved in multiple phases.

The initial phase (Phase 0) corresponds to the current once-through fuel cycle. During this phase, the production rate of waste volume and some of the undesired elements (e.g. plutonium) can be reduced by using a higher burnup fuel. For the initial phase, the fuel development program is interested in the following:

- high-burnup fuels for LWRs (up to ~100 MWd/kg burnup) and

- TRISO fuel for gas-cooled reactors.

The transition to a closed fuel-cycle nuclear economy starts with point A, which marks the beginning of spent nuclear fuel (SNF) partitioning (Phase 1), where uranium (U), cesium (Cs) and strontium (Sr) are separated from the SNF to reduce the volume and short-term heat requirements on the repository. No fuel development is associated with Phase 1.

The start of plutonium (Pu) neptunium (Np) recycling and perhaps a small amount of americium (Am) in thermal reactors marks the start of Phase 2. Primary fuel forms of interest during this phase are:

- Mixed oxide fuels (containing small amounts of minor actinides) for LWRs,
- Am transmutation targets for LWRs,
- Inert matrix fuels (IMF) for LWRs, and
- TRISO fuel containing Pu and other TRU for gas-cooled reactors.

Depending on decisions associated with the amount of high-level waste that will be stored in underground repository(ies), implementation may require a burn-down phase (Phase 3) where the waste must be burned down as the energy generation continues. While some elements (e.g. Pu and Np) may be burned down using thermal reactors, other minor actinides (e.g. Am and Cm) could require dedicated fast-spectrum transmuters. ADS that use fertile-free fuels or low-conversion ratio fast reactors (FR with low CR) that require low-fertile (low U content) fuels are candidates for the dedicated transmuters. In addition to fuel forms used in Phase 2, the fertile-free or low-fertile fuel forms of interest for this phase are:

- Metal,
- Ceramic (nitride, oxide or carbide),
- Ceramics dispersed in metal matrix (CERMET), and
- Ceramics dispersed in ceramic matrix (CERCER).

The TRU composition of these fuels (elemental and isotopic composition) depends on the outcome of the thermal reactor transmutation in Phase 2 and the implementation strategy in Phase 4. For instance, the amount of Pu in the fuel depends on how much of it is destroyed in Phase 2 and how much of it is needed to start the fast reactors in Phase 4.

Finally, once the waste quantities are reduced to desired levels, an equilibrium phase (Phase 4) will be started. In this phase, the reactors take care of their own waste so that waste generation is approximately zero per unit of energy production. For this phase, additional fuel forms of interest are similar to those listed in Phase 3, with a higher fertile component (high conversion ratio fast reactor fuels).

AFCI Fuel Development Scope

Presently, many fuel forms and compositions are being considered within the AFCI fuel development program. The U.S. overall strategy is an optimization problem of multiple variables, some of which are policy related. Typically, systems level analyses accounting for the economic and facility-availability constraints along with the repository capacity, while extending Yucca Mountain storage capacity or by deploying additional repositories, will define the path.

However, the feasibility of the fuel form and its performance characteristics are its technological constraints in the optimization equation. Thus, such constraints must be quantitatively defined with adequate confidence that the specified values are achievable, prior to technical input for additional repositories or alternative fuel cycles (Figure 5-6).

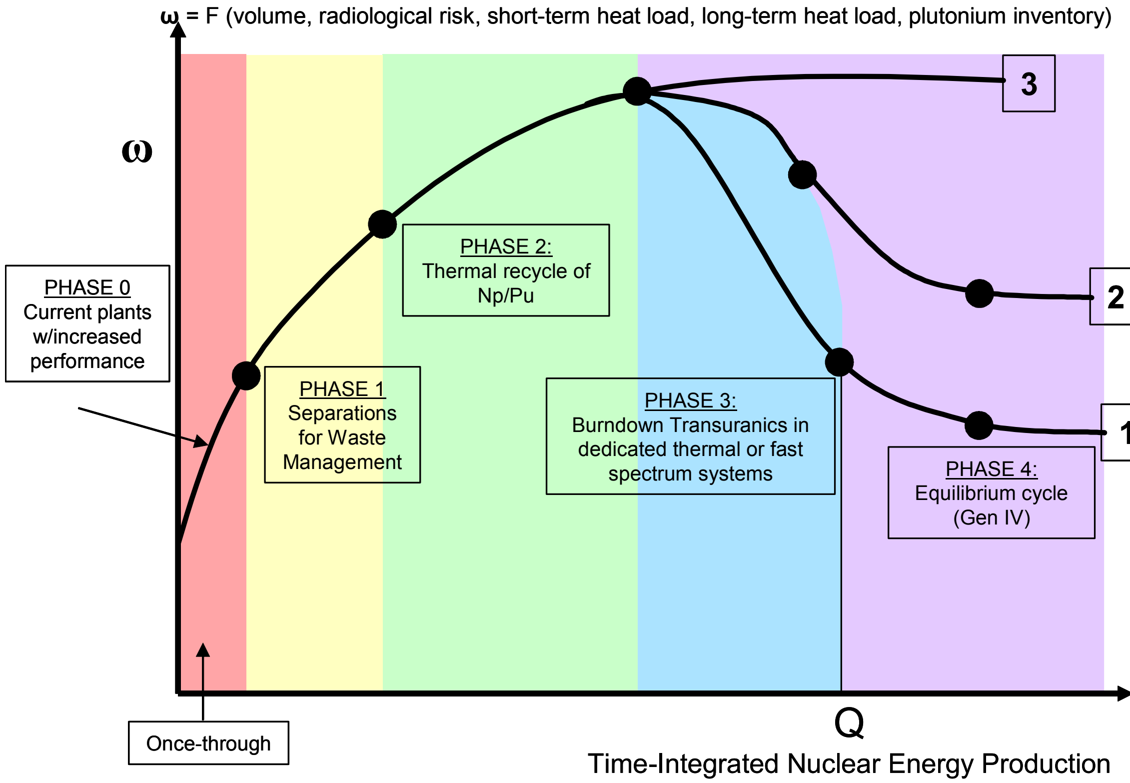

Figure 5-6. AFCI Implementation Phased Approach to Transition to Closed Fuel Cycle

The challenge is to develop a program plan that will meet the program objectives within resource and schedule constraints. There are a number of different approaches that can be taken:

1) **Implement a fuel development and qualification program for all fuel types of interest**. This approach would yield a high confidence result on all potential implementation strategies and would facilitate the decision on the fuel cycle. However, the implementation would be very expensive and time consuming. Even with adequate funding, the qualification program would require a minimum of 15 years and would not meet the objective to provide technical input to a Secretarial decision regarding additional repositories by 2007–2010.

2) **Delay starting the fuel development program until a decision on the fuel-cycle and the associated technologies is made**. A realistic fuel cycle definition and technology selection cannot be accomplished without some knowledge of the feasibility of the fuel(s) needed for implementation. Thus, some early research on all fuel types is needed to provide feasibility input to the system definition studies.

3) **Focus on fuel development for Phases 0 and 2 as shown in Figure 5-6, while delaying any fuel work for later phases.** Similar to option 2, this approach does not

satisfy the program objective because fuel feasibility in all stages must be addressed before a realistic fuel cycle definition can be achieved. Any technological showstoppers or limitations in later phases have an impact on decisions made during earlier phases. Starting a fuel cycle program without due considerations for later options and their feasibility may result in a fuel cycle that is of limited benefit.

4) **Complete some level of R&D for most fuel types in various phases to provide input with adequate technical confidence for fuel cycle definition and technology selection**. This is the most sensible approach to achieve program objectives while keeping fuel development costs within a reasonable range. The challenge for fuel development is to define the amount of early research required for high-confidence input to system level assessments and technology selections within the budget and schedule constraints, which will definitely preclude a qualification program on all fuel types. Without going through a qualification process, 100% confidence in specific fuel performance cannot be achieved. On the other hand, achieving such high confidence is not necessary if system studies properly address the performance uncertainties and technological risks.

Based on these arguments, the fuel development program is gauged to a Technology Readiness Level (TRL) scale, which is presented in the next section.

Technology Readiness Level for Fuel Development. While the definition of the TRL is somewhat arbitrary, it is used as a communication metric on the research progress and cross-comparison of knowledge on various fuel types.

The fuel development plan entails the fabrication and performance for implementing the fuel cycle technologies. To achieve the ultimate goal of deploying these fuels on an industrial scale, both the fabrication and irradiation demonstrations must be completed.

- In *fuel fabrication*, the ultimate goal is to demonstrate the capability of large-scale (industrial) production that meets the nuclear quality assurance (QA) requirements with minimal loss of TRU (the loss criteria will be developed by the systems analyses). If new alloys are needed for cladding the specific fuels, industrial-scale fabrication of clad materials that meet nuclear QA requirements must also be demonstrated.
- In *fuel irradiation*, the fuel should safely withstand at least 20% burnup (20% of initial TRU loading). In mixed oxide fuels aimed for LWR use, the minimum burnup requirement is 45–50 GWd/ton of heavy metal (HM) to be compatible with the current industrial refueling cycles. Demonstration of irradiation performance must include clad materials in a prototypic environment with prototypic fuel materials.

To measure progress for fabrication and irradiation, a TRL scale from 1 through 9 is assigned for three major categories:

- **Concept Development**: Suitable fuel forms for various applications are defined based on first principles and fundamental materials knowledge. Show stoppers are identified, a work-around for show stoppers (both fabrication and irradiation) is defined, and a verification plan is developed. This phase covers TRL 1 through 3 and is completed for almost all fuel forms of interest even though some of the matrix materials for dispersion fuels are still being evaluated under TRL 2 and 3.

- **Proof-of-Principle**: Development using laboratory-scale experiments and analytic extrapolations to full-scale behavior is performed. During this phase, fabrication and characterization tests are performed at 100 g to kg levels. Irradiation tests are typically performed at the pellet to rodlet (~10 cm pins) levels. The proof-of-principle phase covers TRL 4 through 6.
- **Proof-of-Performance**: Large-scale demonstrations are performed leading to final performance specifications, including statistical assessments. This stage includes engineering-scale demonstration of the fabrication process by which the lead test assemblies (LTAs) will be produced. Subsequently, full scale demonstration of fabrication and irradiation performance completes the fuel development. Proof-of-performance covers TRL 7 through 9.

Table 5-2 provides a summary of TRL definitions for AFCI fuel development.

Table 5-2. Summary of TRL Definitions for AFCI Fuel Development

R&D Scale	Fabrication/Testing	R&D Category	TRL
Concept identification	Bench scale	Concept development	1
Concept evaluation	Bench scale	Concept development	2
Concept development & verification plan	Bench scale	Concept development	3
Fuel pellets	Lab-scale	Proof-of-principle	4
Rodlets (≥ 10 cm)	Lab-scale	Proof-of-principle	5
Pins (full-length)	Lab-scale	Proof-of principle	6
Multiple pins in assembly	Engineering scale	Proof-of-performance	7
Lead-test assemblies	Engineering to full-scale	Fuel qualification	8
Fraction of a core	Full scale	Demonstration	9

The scope of the fuel development program is to progressively guide R&D until the demonstration phase is reached. However, the early emphasis over the next 5 to 7 years is to complete the proof-of-principle for various fuel types essential to defining the fuel cycle. Because this information is needed for the Secretarial decision on the need for an additional repository versus deployment of closed-fuel cycle technologies, the proof-of-principle phase of the program must be completed by 2007–2010.

5.2.2 Fuels Development Goals and Objectives

The long-term objective of the fuel development program is to progressively define the R&D and solution strategies for various fuel types of interest in all phases of the AFCI program consistent with the program vision and objectives stated in Section 1.

The program plan and associated goals, objectives, and major milestones are progressive and will be evaluated on a yearly basis because

- fuel types will be updated based on fuel cycle strategies that are defined through systems analyses;
- certain fuel types may be removed from the program as major issues are identified and/or technologies that require them are eliminated from further consideration and;

- based on early knowledge gained and anticipated budget constraints, the emphasis on fuel cycle technologies and required fuels will favor those with the highest potential for success.

Fuel Development Programmatic Objective. Even though the research plan for specific fuel types will be evaluated on a yearly basis, the principle objective of the fuel development program remains the same; which is development of fuels to the point of deployment for the fuel cycle phases defined by systems analyses. However, different fuel types used in all five phases of the program will be developed to different degrees of maturity during the next 10 years.

Fuel Development Programmatic Goals. Within a two-year period, high-level program goals can be divided into two major time-periods, FY2007–2010 and FY 2014.

<u>FY 2007-FY 2010 Goals</u>

- As part of technical input for the Secretarial decision on the second repository, complete the proof-of-principle (TRL 6) for the main fuel types required for all five phases of the fuel cycle Figure 5-6). The feasibility assessment includes fabrication processes, irradiation performance, and an initial assessment for the deployment cost.
- Complete production of the baseline TRISO fuel for HTGR (VHTR), initial shakedown testing in ATR, and initiate the multi-module testing of the final particles.

Depending upon the implementation scenario chosen, the following goals will be established.

<u>FY 2014 Goals</u>

- Complete the initial qualification program for LWR fuels (ultra-high burnup, mixed oxide and/or IMF), and be ready to initiate the LTA irradiation in commercial LWRs.
- Consistent with the Gen IV technology decision, complete the comparative research for down-selection of the transmutation fuel form for use in fast-spectrum reactors and ADS.
- Complete the TRISO fuel qualification program for HTGR (VHTR) to support technology deployment.

5.2.3 Fuel Development Major Milestones

Until the definition of the fuel cycle is completed and a decision is made to change from the current once-through fuel cycle strategy, the program plan will focus on the near-term milestones (until FY 2010).

Fuel development involves multiple processes as follows:

- Powder preparation,
- Pressing,
- Chemical processing (to desired chemical form with required stoichiometry),
- Thermodynamic/mechanical processing (solid solution versus dispersion),
- Sintering,
- Pellet pressing,

- Pellet machining,
- Pin fabrication and bonding, and
- Assembly fabrication.

During the proof-of-principle phase (TRL 4 through 6), the fabrication processes will be tested at 100 g/yr throughput levels for fabricating less than 100 pellets per year. In addition to fabricating actual pellets at laboratory scale, surrogate materials will be used for phenomenological assessment of various parts of the flow sheets. Mechanistic models will be developed and benchmarked to analyze the overall fabrication flowsheets. Engineering analyses using the models and separate effect tests with surrogates will be used to assess the feasibility of large-scale fabrication (on the order of 100 kg of TRU /yr throughput), by applying appropriate rate scaling. Based on such analyses, a pre-conceptual fuel-fabrication plant design will be developed to:

- Assess the flow-sheet performance with specific emphasis on potential losses and scrap and
- Develop a preliminary cost estimate for such a plant.

At present, the assumption is that no new clad alloys will be developed for the fuel types of interest. The cladding research will primarily focus on finding the most appropriate material among the alloys currently available.

Engineering scale demonstration will be performed (TRL 7) once the primary fuel candidates are selected for the different phases of the implementation (after FY 2007). The exact throughput levels for the engineering scale demonstration will be decided after the flowsheets are developed and fabrication equipment identified. The fuels used for the LTA will most likely be reproduced from the engineering scale demonstration.

Fuel *irradiation performance* is affected by many variables including the microstructural, mechanical and chemical properties stemming from the fabrication processes. During irradiation, it is important to match the fuel temperature and the temperature gradients, along with the fission rates. To approximate the thermal conditions, the reactors must have similar power densities (fissile density, neutron flux and neutron spectrum), along with matching thermal-hydraulic boundary conditions (heat transfer coefficients, gap size and bond material). Damage in the fuel matrix is strongly dependent on the neuron flux and spectrum, and to adequately test fuel-clad interactions, the interface conditions must also be properly simulated. The behavior of the clad material depends on the clad temperature, pin pressure, neutron flux and spectrum.

There is no simple scaling law for testing the fuel under non-prototypic conditions allowing extrapolation of the overall performance to prototypical conditions. However, separate effect tests can be performed by adjusting multiple variables to match the desired conditions for a given phenomenology. For example, the effects of burnup on a fast reactor fuel can be tested in a thermal reactor by varying a number of design parameters to match the thermal conditions as long as synergistic phenomenological effects are well understood (e.g. burnup plus radiation damage effect or burnup plus beginning of life (BOL) composition/enrichment effects). This requires carefully designed separate effect experiments, along with a fundamental understanding of the synergistic effects through modeling. In some cases, bounding experiments can be designed where some of the phenomenology is conservatively simulated to show the extreme effects.

During the proof-of-principle phase, the program will

- Fabricate and characterize fuel pellets of varying compositions (TRL 4);
- Perform out-of-pile testing of these pellets (thermal, FCCI) (TRL 4 and 5);
- Perform irradiation testing and post-irradiation examination (PIE) on fuel pellets (~100) using rodlets to a full-length pin. Most of the irradiation will be performed in a thermal test reactor using phenomenologically targeted separate effect tests, but some testing will also be conducted in fast reactors (for fast reactor fuels) through International collaborations (TRL 5 and 6); and
- Perform phenomenological analyses to investigate the impact of synergistic effects and assess fuel feasibility under full prototypic conditions (TRL 6).

For irradiation performance, LTA testing under prototypic reactor conditions would be needed for qualification of the fuels (TRL 8). In order to demonstrate the irradiation performance of the proposed fuels, multiple full-size pins under prototypic irradiation and thermal-hydraulic conditions must be tested (TRL 7). These activities will not start until after the Secretarial decision in the 2007–2010 timeframe.

Fuel Development Performance Measure for FY 2007–FY 2010

The following are the performance measures for the FY 2007–FY 2010 time-frame:

- Complete feasibility studies (proof-of-principle) for various fuel types by:
    - Laboratory-scale fabrication testing (~100 pellets/year),
    - Engineering analyses for full-scale fabrication (~10 ton HM/yr),
    - Pellet characterization with varying compositions (~100 pellets/yr),
    - Out of pile testing of pellets (thermal, FCCI),
    - Separate effect irradiation testing and PIE on pellets (total of ~100 pellets), and
    - Phenomenological assessment of irradiation performance in a prototypic environment and confidence level assessment.

Fuel Development Program Elements

The current plan is tailored for the research phase of the fuel development program with the program elements described below.

Integration and Analyses. Efforts include national program integration, analyses support and International collaborations. *National program integration* is aimed at defining and implementing the research plan. In addition to the activities of the national Technical Director (NTD), the fuel development working group (FDWG) activities are covered under this program element. *Analyses support* covers the analytical activities necessary for developing and implementing the R&D plan, and for defining the functions, requirements and performance envelopes for the various fuels types. *International collaborations support* the DOE in identifying and implementing International collaboration agreements. Activities under this element define and coordinate the work performed in collaboration with the International partners with the actual research being performed under the subsequent appropriate elements. Finally, *University collaborations* consist of directed university contracts supporting university professors and associated students performing research at universities or national laboratories, in performance of the AFCI fuel development tasks.

Transmutation Fuel Development. Encompasses the fabrication, characterization, out-of-pile testing, process optimization and modeling of various advanced fuels forms that contain transuranic elements (Pu, Np, Am, Cm). *Oxide fuels* covers both the LWR and fast-spectrum fuels, even though the research emphasis is on LWR fuels. *Nitride fuel* research is focused on fast-spectrum fuels that can be used in liquid-metal cooled (sodium or lead-alloy) fast-spectrum transmuters. *Metal fuel* research considers liquid metal cooled fast spectrum applications and is primarily applicable to sodium-cooled transmuters. Presently, *Carbide fuels* are not being considered for direct transmutation applications (burn-down phase), however they may be required for one of the Gen IV systems (e.g. gas-cooled fast reactor) during the equilibrium phase. *Inert matrix fuel* research is directed towards transmutation in LWRs (ALWRs) using uranium free fissile material, plutonium, plus possibly minor actinides, in an inert matrix. *Dispersion fuels* can be in the form of CERCER (ceramic fuel in a ceramic matrix) or CERMET (Ceramic fuel in a metal matrix). They are the more advanced fuel forms with a good high-burnup potential, and thus are very attractive for transmutation applications even though fabrication and testing of these fuels will require more extensive research. The U.S. program is considering the fast gas reactor (FGR) for dispersion fuel development, but through collaboration with CEA and the Institute for Transuranium Elements (ITU), Karlsruhe, Germany, the fertile free version of the dispersion fuels are also being addressed. Finally, TRISO fuel research is aimed at expanding the basic TRISO fuel development performed under the Advanced Gas Reactor fuel development, to transmutation applications by investigating the TRU kernels and advanced coating options.

Transmutation Fuel Irradiation. Covers scoping irradiation tests performed in the *Advanced Test Reactor* (ATR) for the fuel types discussed above. Activities associated with *irradiation testing* include the test design, test vehicle fabrication, irradiation services, and transport to the PIE facilities. Any specific *test facility development* (design and construction) addresses capabilities such as the fast flux booster, special coolant loops, and advanced instrumentation

Transmutation Fuel PIE. Covers the Post-Irradiation Examination (PIE) for transmutation fuels, primarily irradiated in ATR but also in foreign facilities such as the Phenix fast spectrum reactor in France. *Therma-_reactor fuel PIE* addresses mixed-oxide, IMF and TRISO fuels for transmutation applications only. *Fast-reactor fuel PIE* addresses all other fuel types used in fast-spectrum transmutation applications.

Advanced Gas Reactor Fuel. Covers the initial fuel qualification activities for fuel to be used in the VHTR demo. A detailed separate development plan exists for this activity.[3] *Fuel manufacturing* addresses the work necessary to produce coated particle fuel that meets the fuel performance specifications. *Fuels and materials irradiation* consists of irradiation testing in ATR. *Safety testing and PIE* provides the facilities and processes to measure the fuel

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3 "Technical Program Plan for the Advanced Gas Reactor Fuel Development and Qualification Program, " ORNL/TM-2002/262.

performance under normal and accident conditions. *Fuel performance modeling* addresses the structural, thermal, and chemical processes that can potentially lead to fuel failure. Finally, *fission product transport and source term* addresses transport of the fission products through the fuel, and establishes the basis for the source term computations during normal and accident conditions.

Small Modular Reactor Fuel. Covers fuel development of a Gen IV concept: the lead alloy cooled long-life core reactor. *Fuel design and analyses* defines the fuel functions, requirements, and geometry. *Out-of-pile testing* develops the fabrication processes and characterization activities. *Fuel Irradiation and PIE* includes the scoping irradiations and subsequent PIE leading to a fuel qualification program.

LWR High-Burnup Fuels. Covers activities for developing high-burnup fuels (80–100 MWd/kg) for use in LWRs, which are fertile fuels. *Fuel design and analyses* defines the fuel functions, requirements, and geometry. *Out-of-pile testing* develops the fabrication processes and characterization activities. *Fuel irradiation and PIE* includes scoping irradiations and subsequent PIE leading to a fuel qualification program.

Key Milestones

The major milestones for a 10-year period are described below and summarized in Figure 5-7. All important FY 2004 milestones are presented for each program element. FY 2005–FY 2010 milestones are elaborated, but each program element is not addressed because subsequent work depends on the availability of resources in various program elements. After FY 2010, subsequent milestones depend on program direction based on the Secretarial Recommendation; therefore, a limited number of more general milestones are shown for the period.

FY 2004

The major FY 2004 milestones are as follows, sorted by fuel development program elements:

<u>National Program Integration</u>

- Publish a detailed implementation plan for fuel research necessary as technical input to support the Secretarial decision (yearly update thereafter).
- Establish the modeling framework for the various fuel types of interest.
- Establish the project management structure for FUTURIX after an implementation agreement is signed.
- Establish framework or arrangement for the MILE collaboration with ITU and the Paul Scherrer Institute (PSI) for the Inert Matrix fuel after an implementation agreement or arrangement is signed.

<u>Transmutation Fuel Development</u>

- Complete LWR-1a (low burnup) fuel pins and ship to ATR for irradiation.
- Complete LWR-1b (high-burnup) fuel pellet fabrication and characterization.
- Complete AFC-1 fuel pin fabrication for AFC-1 low and medium burnup experiments in ATR for metal and nitride fuels.

- Complete AFC-1 fuel pellet fabrication and characterization for high-burnup experiments in ATR for metal and nitride fuels.
- Provide input to CEA on metal and nitride fuels for FUTURIX research report.
- Complete test modules for GFR-F1 materials test.
- Complete initial feasibility assessment of GFR fuel options.

Transmutation Fuel Irradiation

- Complete LWR-1a (low burnup) irradiation and ship pins for PIE.
- Prepare for LWR-1b (high-burnup) irradiation.
- Complete AFC-1 low and medium burnup irradiations for metal and nitride fuels and ship pins for PIE.
- Prepare for AFC-1 high-burnup irradiation for metal and nitride fuels.
- Complete GFR-F1 materials irradiation and ship for PIE.

Transmutation Fuel PIE

- Prepare for starting LWR-1 (low burnup) PIE in the first quarter of FY 2005.
- Prepare for starting the low and medium burnup PIE for metal and nitride fuels in the first quarter of FY 2005.

Advanced Gas Reactor Fuel

- Finalize irradiation test specifications for the AGR-1 fuel shakedown test.
- Complete fabrication of the 350-μm diameter depleted UO_2 kernels.
- Manufacture NUCO and LEUCO kernels.
- Reproduce German reference coating properties and coat batches of LEUCO kernels for irradiation.

Small Modular Reactor Fuel

- Complete high-level functions and requirements, an assessment of various fuel forms and provide a matrix for additional development needs.

LWR High-Burnup Fuel

- There are no milestones for FY 2004

FY 2005

The major FY 2005 milestones are as follows:

- Complete fuel fabrication modeling and optimization for LWR TRUMOX fuels.
- Start irradiation of high and medium burnup TRUMOX fuels.
- Complete PIE of the low burnup TRUMOX fuel.
- Complete fabrication and characterization of TRUMOX fuel pellets for MILE irradiation.

- Complete PIE on low and medium burnup nitride and metal fuels.
- Start irradiation of high-burnup metal and nitride fuels.
- Complete fabrication and characterization of FUTURIX pellets (nitride and metal) and ship to ITU.
- Complete fabrication of initial dispersion fuel samples for ATR irradiation.
- Complete fabrication of initial IMF samples for ATR and MILE irradiation.
- Complete initial planning and test program for high-burnup fuels.
- • For AGR milestones, see Reference 1.

FY 2006

The major FY 2006 milestones are as follows:

- Complete PIE of medium burnup TRUMOX fuels.
- Complete irradiation of high-burnup TRUMOX fuels.
- Complete IMF and dispersion fuel irradiation in ATR.
- Start irradiation of the first pin in MILE.
- Complete fabrication of the second pin for MILE irradiation.
- Complete the final analyses and feasibility assessment for metal and nitride fuels for transmutation.
- Fabricate high-burnup LWR fuel samples (which maximize repository benefits) for ATR irradiation.
- Start FUTURIX irradiation.
- For AGR milestones, see Reference 1.

FY 2007

The major FY 2007 milestones are as follows:

- Provide Fuels Development input to report for Secretarial Recommendation on need for second repository.
- Complete PIE of high-burnup TRUMOX fuels.
- Complete PIE on IMF and dispersion fuel.
- Start irradiation of the second pin in MILE.
- Complete feasibility assessments on transmutation fuel forms (metal, nitride, dispersion, oxide and IMF).
- Complete the point design of fuel fabrication facility for cost estimating purposes.
- For AGR milestones, see Reference 1.

FY 2008

The major FY 2008 milestones are as follows:

- Complete irradiation of the first pin in MILE.
- Complete feasibility assessment of TRISO as transmutation fuel.
- Complete fuel feasibility report for Secretarial recommendation.
- Complete FUTURIX irradiation.
- Complete the cost estimate of the fuel fabrication facility.
- For AGR milestones, see Reference 1.

FY 2009

The major FY 2009 milestones are as follows:

- Complete fabrication of fast spectrum fuels to be inserted for comparative ATR irradiation (input to down-selection study).
- Complete fuel fabrication of LWR fuels (MOX, IMF, high-burnup) to be inserted as a comparative ATR irradiation (input to down-selection study).
- Fabricate TRISO transmutation fuel for ATR irradiation.
- For AGR milestones, see Reference 1

FY 2010

The major FY 2010 milestones are as follows:

- Complete FUTURIX PIE.
- Complete ATR irradiation of fast spectrum fuels (input to down-selection study).
- Complete ATR irradiation of LWR fuels (input to down-selection study).
- Complete ATR irradiation of TRISO particle fuel.
- Complete PIE of the first MILE pin.
- For AGR milestones, see Reference 1.

FY 2011

The major FY 2011 milestones are as follows:

- Complete PIE after ATR irradiation of fast spectrum fuels (to feed the down-selection study).
- Complete PIE after ATR irradiation of LWR fuels (to feed the down-selection study).
- Complete PIE after ATR irradiation of TRISO particle fuel.
- Complete PIE of the second MILE pin.
- For AGR milestones, see Reference 1.

- Complete pre-conceptual design of the transmutation fuel fabrication facility.

FY 2012

The major FY 2012 milestones are as follows:

- Downselect transmutation fuel form.
- For AGR milestones, see Reference 1

FY 2013

The major FY 2013 milestones are as follows:

- Start LTA preparations for the selected fuel forms and associated fabrication processes.
- Complete conceptual design of the transmutation fuel fabrication facility.

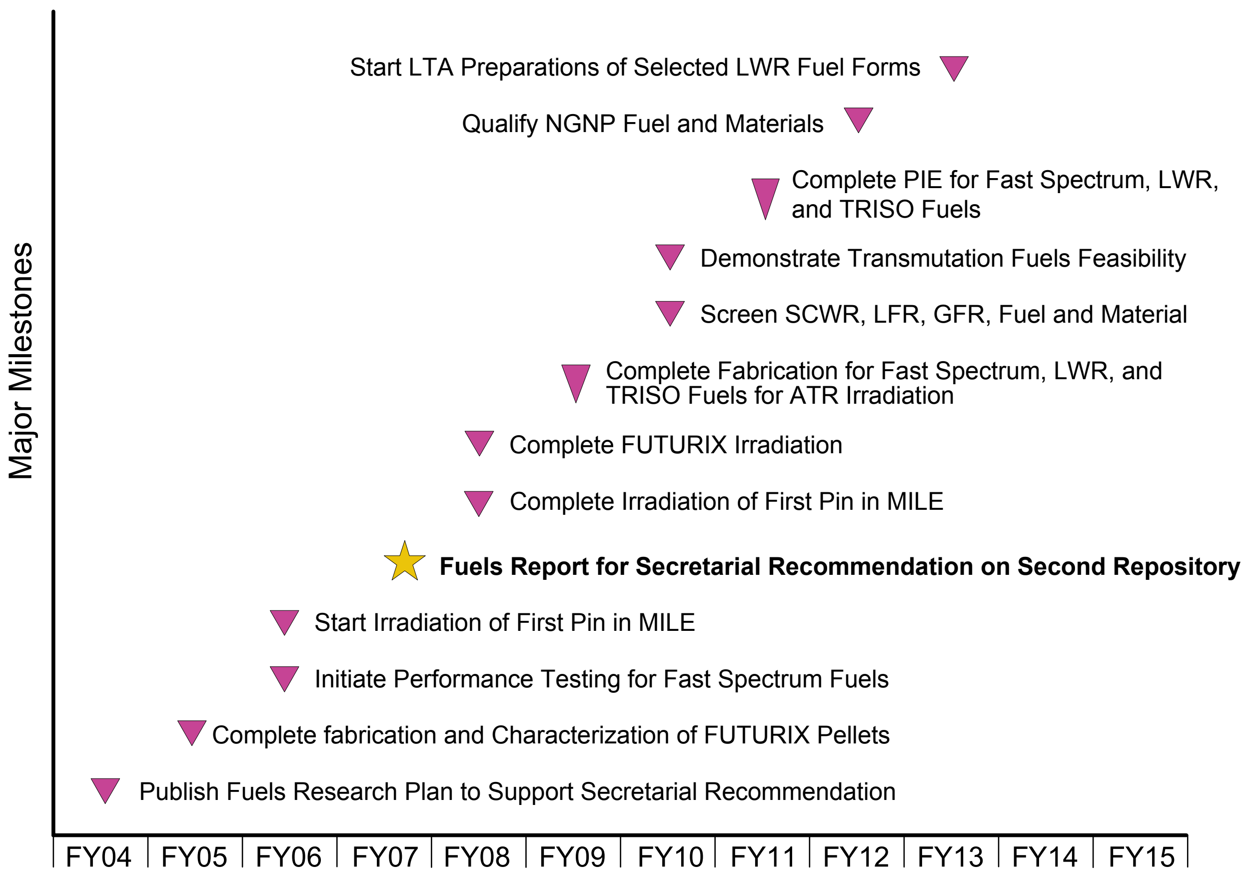

Figure 5-7. Fuels Development Milestones

5.3 Transmutation Engineering

5.3.1 Transmutation Engineering Overview

Transmutation engineering provides critical R&D to support the AFCI transition fuel cycle, AFCI equilibrium fuel cycle, and Gen IV technologies, specifically in the areas of: 1) physics, 2) materials, 3) coolant technology, and 4) ADS. Transmutation is a process by which long-lived radioactive species, particularly actinides (but also certain fission products), are converted to short-lived nuclides by either fission or neutron capture. By changing the decay timescale from millennia to hundreds of years, toxicity and heat load challenges to the U.S. geologic repository fall into the realm of well-known engineering practices, and thus become easier to solve with better certainty of success. In the transition fuel cycle the AFCI, if implemented, could destroy up to approximately 60 percent of the plutonium and neptunium contained in civilian spent fuel with multiple recycle technology. In the equilibrium fuel cycle, AFCI fast spectrum systems (either reactors, ADS, or a combination) could be expected to destroy the balance of the plutonium and other actinides of concern. Analyses are underway to determine how efficiently AFCI equilibrium fuel cycle Gen IV fast reactors and ADS can perform transmutation. At the same time, a significant amount of research is being conducted in Europe and Japan in the area of partitioning and transmutation systems. In their view, the ADS will play a major role in the destruction of higher actinides. Thus, there is a strong motivation to collaborate with the foreign research establishments and leverage our funding in this area.

A decision on the transmutation path forward should be made as early as FY 2007, but no later than FY 2010. Until that time, development activities will continue on ADS within the AFCI program, and on fast spectrum reactors within Gen IV to raise the level of technological maturity to support informed decisions. For ADS and transmutation R&D, the AFCI program plans to influence and benefit from research performed in other countries as a means of keeping this technology path a viable option.

5.3.2 Transmutation Engineering Goals and Objectives

The top-level objective of the Transmutation Engineering technical area is to develop engineering data and designs for transmutation of minor actinides and long-lived fission products so that informed decisions can be made in the next five years on transmutation technologies, and a path forward can be developed for implementation. This will support a Secretarial recommendation on the technical need for a second repository by December 31, 2007. In support of these objectives, proof-of-principle information must be developed in areas not supported in the fuels, separations, Gen IV, or other DOE-NE research programs. In the near-term, transmutation engineering activities are focused in the areas of nuclear data and codes, coolants and corrosion, structural materials, and accelerator-based transmutation. Subsequent to the decision on transmutation technologies and a successful proof-of-principle phase, engineering development and demonstration will be performed to provide proof-of-performance in support of deployment of transmuter technology.

As discussed previously, the overall program objectives are driven by benefits to the repository and supporting needs as required for the Gen IV fast reactor transmutation system. In this regard, transmutation engineering *primarily* supports the equilibrium fuel cycle with respect to the reduction in long-term heat load, environmental risk, and radiotoxicity objectives. Some of the engineering data will also support transition fuel cycle objectives, especially in the area of physics, where experimental measurements and evaluation of key nuclear cross sections will reduce uncertainties in transmutation rates.

5.3.3 Transmutation Engineering Major Milestones

In addition to supporting the overall program objectives, transmutation-engineering activities provide essential information to key program decisions that will be made in the near-term for both the AFCI and Gen IV programs. These key decisions and the transmutation-engineering tasks that support them are shown in Figure 5-8 below. The major transmutation-engineering milestones for the next ten years are:

FY 2004

- Document Gen IV fast spectrum materials development requirements.

FY 2005

- Perform physics calculations on LWR fertile-free fuels to allow testing of the fuels in cooperation with the European Community starting in FY 2006 in a European PWR.
- Obtain data from transmutation experiments carried out under multilateral international agreements with France, Switzerland, the European Community, and Russia--should an agreement have been finalized in the prior two years.

FY 2006

- Initiate physics analysis of existing fast reactor cross-section data to reduce uncertainties among the most important transuranic actinides (neptunium, americium, curium, and plutonium) to permit accurate determination of potential material consumption per irradiation cycle needed to design economic fast spectrum transmuters.
- Complete 6,000 hour lead-alloy corrosion tests in the lead-alloy technology development loop (DELTA) at Los Alamos National Laboratory (LANL), testing of materials of interest to advanced reactor and accelerator-driven transmutation concepts, and recommend if advanced materials development work, such as the need for protective coatings, is needed for advanced transmuter concepts.
- Transmutation engineering, working with systems analysis, will complete a study on the implementation strategy path(s) forward to carry out the decision if the U.S. can forgo, or delay, the technical need for a second repository; providing the necessary information for a Secretarial recommendation by the end of CY 2007.

FY 2007

- Complete a report on transmutation related results of international cooperation performed to date (and planned) in order to be used as part of the database available for the Secretarial recommendation, and for future proof-of-performance implementation plans.
- By the end of FY 2007, complete the down-selection of reference structural materials and coolant for the transmutation system design.
- By the end of FY 2007, complete implementation of the materials test station and the fast flux booster for initiation of proof-of-performance testing.

FY 2008

- Initiate transmutation technology proof-of-performance testing that is needed to affect transmutation systems implementation strategies for the next two decades.

FY 2009

- Provide the final report on optimal transmutation systems and the final report on the MEGAPIE experiment.

FY 2010

- Provide the final report on the TRADE experiment that will be completed in Europe.

FY 2011

- Provide the final report on the structural design criteria.

FY 2012

- Complete the upgraded physics database for transmutation systems.

FY 2014

- Demonstrate the performance of materials needed for Gen IV transmuter systems.

Development of a baseline of the AFCI transition fuel cycle and AFCI equilibrium fuel cycle implementation strategies and the selection of a Gen IV fast reactor concept are expected in the FY 2007 to FY 2010 timeframe. For purposes of this plan, the earlier date of FY 2007 is assumed for these technology selections. Prior to that time, preliminary baselines will be established on an annual basis. The technical integration area will integrate the information provided by systems analysis and the major technology areas (fuels, separations, and transmutation engineering) to help make these decisions. It is understood that, as these decisions are made, transmutation engineering activities will evolve to remain sharply focused on essential research areas.

As currently envisioned, Gen IV in the U.S. will continue with two priorities: the first priority is for a near-term demonstration of an advanced, efficient reactor that will produce either electricity or hydrogen. The second priority is long-term and will be focused more on sustainability, transmutation, and fuel utilization. The reference first priority system is the Very High Temperature Reactor (VHTR) with thermal-chemical water splitting for hydrogen production. The second priority system decision is still open, but most likely will be a fast-spectrum reactor. Fast reactor systems under consideration by the Gen IV International Forum include sodium, gas, and lead-cooled systems.

Selection of the Gen IV reactor technologies for future nuclear power generation will drive AFCI transmutation technology development. The first priority system must have the capability to destroy plutonium to meet the transition fuel cycle requirement of 60% Pu burn. The VHTR, for example, will meet that need because of its potential for deep burn of plutonium. For equilibrium fuel cycle, a fast-spectrum system is needed to meet the transmutation goals. This may be a Gen IV fast reactor and/or a dedicated fast-spectrum system. At this time, a fast reactor system appears preferable because of its ability to efficiently produce power while meeting transmutation objectives. However, system studies completed to date indicate that a fast reactor system optimized for transmutation may sacrifice some economic advantages. A dedicated fast-spectrum system may be a better choice for transmutation, but more R&D is needed to determine the optimal system. For these reasons, research into dedicated fast-spectrum systems will be carried forward until sufficient data is available to make a better-informed decision in the FY 2007 timeframe and beyond.

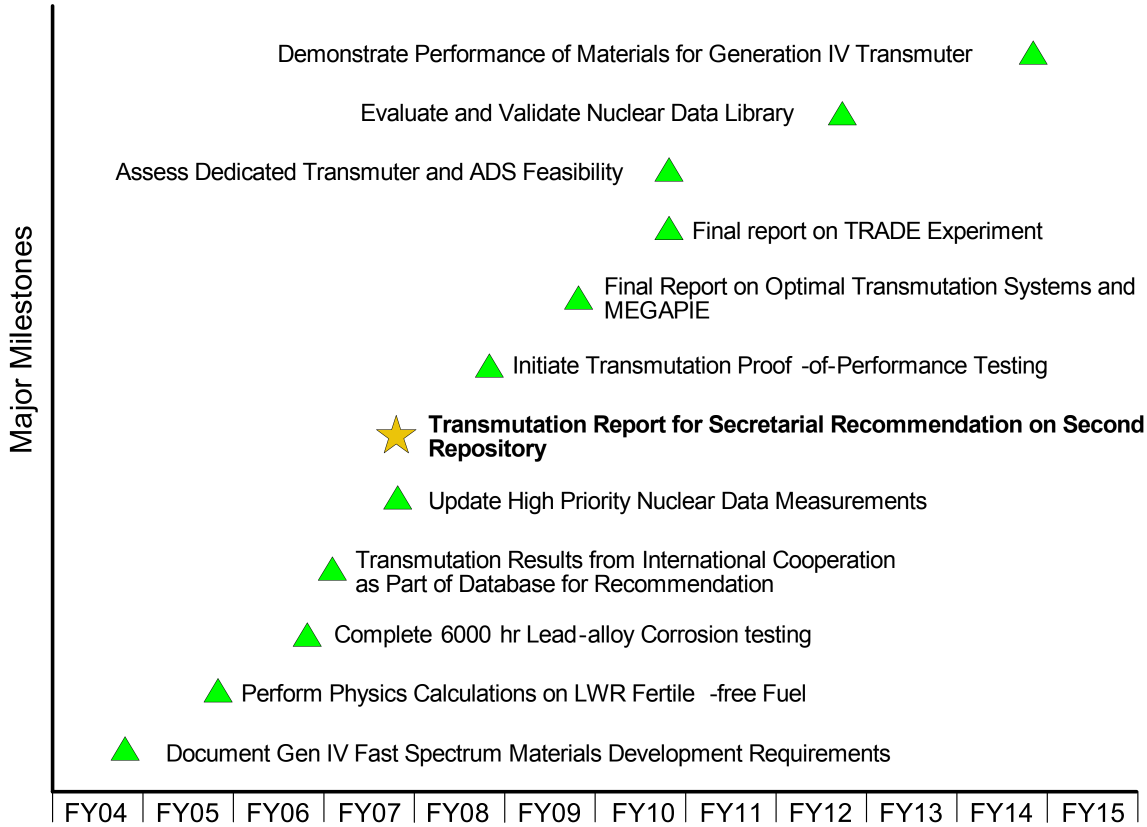

Figure 5-8. Transmutation Engineering Milestones

5.3.4 Transmutation Science and Engineering Summary of Activities

In FY 2007, information provided by Transmutation Engineering and other advanced fuel cycle activities will provide support for key program decisions. This support for the decisions in FY 2007 and beyond is summarized below for each of the major activity areas: physics, materials, and ADS.

Transmutation Physics. The transmutation physics task will provide the computational tools and data needed for accurate predictions of the overall neutronic performance of transmutation systems. The task will support decisions for transition fuel cycle and equilibrium fuel cycle, as well as for selection of Gen IV fast reactors. The transmutation physics task will also include participation in international transmutation projects to provide expertise to the international programs and gain knowledge and experience in transmutation applications. The products of this work will be a verified set of nuclear design tools cross section data sets. In addition, the knowledge base to use them with an understanding of the quantified uncertainty, as applicable to transition fuel cycle, equilibrium fuel cycle, and Gen IV systems, will be provided. The uncertainty in the design and analysis of nuclear systems has a direct impact on the margins that must be applied to operate the systems safely. The larger the margins the more expensive it is to operate a facility per unit of transmutation or electrical cost. The goal is to reduce and quantify the uncertainty so that meaningful assessments can be made.

Transmutation physics activities include development of computer programs (or codes), experimental measurements of cross-sections and reactivity feedback coefficients, evaluation of cross-sections for inclusion in nuclear data files, and performance of benchmarks and validations. The data and codes are required regardless of the technologies chosen for transmutation. Data will be obtained for thermal, epithermal, and fast-neutron spectra to support the technology decisions needed in AFCI transition fuel cycle, AFCI equilibrium fuel cycle, and Gen IV. Cross-section data obtained from experiments and evaluations will be used to reduce the uncertainty in transmutation rates for the minor actinides and, therefore, directly support the technical decisions. Today, there is almost no data on the temperature feedback coefficients for the minor actinides. Data obtained in this area supports the development of the licensing case for the transmutation fuels and will, therefore, be used in determining the overall feasibility of the various fuel compositions. As part of the nuclear data effort, gas production (primarily helium) measurements will be made from isotopically-pure minor actinide samples to support the fuel development effort. Finally, code validation and benchmark efforts will continue to provide accurate analysis tools for physics and safety calculations. Tasks include:

<u>Cross-Section Measurements</u> **-** Nuclear cross-section data will be measured for 11 critical isotopes of Pu, Np, Am, and Cm.

<u>Nuclear Data Evaluations</u> **-** The nuclear cross sections in the Evaluated Nuclear Data File (ENDF) evaluated data libraries will be updated for about 20 actinides. Data uncertainties will be included, as will the results from cross section measurements above.

<u>Nuclear Code Development</u> **-** MCNPX and VARIANT are probabilistic and deterministic codes used for fuel cycle assessments. They will be maintained and upgraded in terms of accuracy, speed, and usability so that system studies, design analyses, and safety analyses can be accomplished effectively.

<u>Materials Cross-Sections</u> **-** Nuclear materials behaviors depend on their response to high fluxes of neutrons and protons, notably gas production and atomic displacements. This activity will measure gas production in structural materials and fuels and benchmark atomic displacement calculations.

<u>Benchmark Nuclear Codes</u> **-** The life cycle of a fuel is calculated iteratively between flux conditions and burnup, which changes the flux conditions. This task will benchmark key code suites to long-cycle burnup data available from fast and thermal flux systems to improve the accuracy for transition fuel cycle, equilibrium fuel cycle, and Gen IV performance prediction and design.

Transmutation Materials. Transmutation materials activities are divided into two parts: the development, testing, and modeling of structural materials to be used in the transmuter (a Gen IV fast reactor or possibly a fast spectrum system coupled with an accelerator) and research and testing of coolant technologies that can be used in these options.

Structural Materials. It is essential to understand that structural materials degradation in the proposed irradiation environments limits the fuel burnup and, therefore, affects transmutation efficiency. To support the technology down-selection decision, the database and an understanding of the behavior of materials under irradiation will be developed, and the material lifetimes for various transmutation systems will be quantified. In addition, an accurate evaluation of material properties (e.g., strength, fatigue, ductility, etc.) under irradiation will be provided. Modeling efforts will provide a mechanism to extrapolate material behavior beyond the range of the data. The mechanisms for material failure and lifetime are very similar for fast-spectrum critical systems and ADS. Therefore, the data and models being obtained for mixed-particle (neutron and proton) systems are reciprocally applicable and will be used as bases for further development activities. Many of the transmuter designs must operate at very high temperatures (600˚C and above). This will be a major focus of the structural materials testing effort. A substantial part of the structural materials effort may include construction of a test station capable of delivering high fast neutron fluxes to perform materials irradiations. Tasks include:

- Testing of existing irradiated materials (including the Fast Flux Test Facility (FFTF));
- Irradiation testing of prototype materials, including:
  - Design and construction of a materials test station at the Los Alamos Neutron Science Center,
  - Development of an irradiation test program, and
  - Obtaining and analyzing irradiated materials from foreign reactor and accelerator programs;
- Development of a Materials Handbook;
- Development of materials design criteria for transition fuel cycle, equilibrium fuel cycle, and Gen IV materials; and
- Development of validated models for irradiation behavior that can then be used for science-based predictions of material performance.

Coolant Materials. Coolant technology is focused on the development of lead-alloy heat-transport system materials and components. Materials development for sodium-cooled reactors and advanced gas reactors will be performed in Gen IV. The development of lead-alloy technologies and applications (DELTA) lead-bismuth test loop at LANL is the primary facility for this research. The loop is being used to perform corrosion, erosion, compatibility, thermal hydraulic, thermodynamic, radiation environment effects and instrumentation tests, with the support of off-line development of sensors, control systems, measurement and impurity removal techniques, and modeling. In addition to U.S. research, the facility is being used for international collaborations investigating lead coolant technologies and the efficacy of specific components and sensors. Long-term corrosion tests will be performed to systematically assess the performance of materials during the initial stage of oxide formation. Testing and analysis of specimens, component performance over time and under varying conditions, and lifetime limits will be determined. Development and testing of materials with enhanced corrosion resistance through special alloying and surface treatment will take place concurrently. Materials will be screened and assessed for high temperatures and coolant technology needs beyond oxygen control. Heat transfer and thermal-hydraulic tests for reactor (e.g., fuel assembly to coolant heat transfer) and spallation target designs will be planned and performed. For the candidate fuel options, compatibility of coolant with fuel cladding and fuels will be investigated. The effects of radiation on corrosion, activation of corrosion products and mitigation strategies, and radiation and spallation product influence on coolant chemistry and mitigation strategies will be studied. These effects will first be studied with surrogates and in simulated environments, and later in integral irradiation campaigns. If necessary, the lead-alloy coolant in the DELTA loop can be changed to pure lead for Gen IV materials screening and coolant technology assessments. Because of the need for similar information to support Gen IV, this research area is expected to have partial support provided by Gen IV, which is depicted in the budget tables. The coolant materials tasks are to:

- Develop a lead-alloy coolant applications handbook based on DELTA test loop operation, experience, and international collaborations;
- Determine a baseline performance envelope;
- Down-select optimum alloys and/or coatings for use in lead and lead-bismuth systems;
- Recommend preferred methods for the control of oxygen to mitigate corrosion;
- Develop and test a high temperature radiation hardened oxygen sensor; and
- Conduct radiation environment effects studies (corrosion product activation and spallation products, including polonium accumulation and removal).

ADS and International Cooperation. Transmutation ADS activities include the development and testing of spallation and transmutation target technologies, physics and engineering of coupled (accelerator/multiplier) systems, development of the safety case, development of a reliable accelerator, and development of operation strategies. This research is being accomplished primarily through participation in international programs and projects in which significantly more ADS-related research is being performed. Target technology development will proceed through support of the MEGAPIE project at the Paul Scherrer Institute in Switzerland. This project will field a lead-alloy spallation target in a 1-MW proton beam by FY 2006. The U.S. is providing lead physics and on-site mechanical engineering design support. In return, the U.S. will receive all data and test results from the project and gain experience in the construction of a flowing lead-bismuth spallation target. To develop strategies for the safe operation of coupled accelerator and sub-critical reactor systems, the U.S. will collaborate on the TRADE project if it is approved for construction by the European Union, which will begin testing a coupled-proton accelerator and TRIGA reactor in Italy in FY 2006. Testing will occur at sufficient power to obtain data on power and temperature feedbacks in a coupled system. Operation and startup procedures for coupled systems will be developed. As part of the collaboration, the U.S. will provide experimental physics support, accelerator design review, and target design support. To better understand the safety basis for coupled systems, the U.S. intends to collaborate on the XADS project (a European Commission ADS demonstration project). If approved, this project will design a 100 MW-class sub-critical reactor driven by a medium-energy linear proton accelerator, and begin construction in FY 2006. The ADS tasks are to:

- Participate in the MEGAPIE experiment by providing design engineering and reviews,
- Support the TRADE test,
- Work with the XADS project team to develop a safety basis and provide accelerator cavities engineering, and
- Prepare an ADS technology report addressing the ADS “state-of-the art.”

5.4 Systems Analysis

5.4.1 Systems Analysis Program Element Overview

Systems Analysis guides the other technical areas by providing the models, tools, and analyses needed to define the best deployment options and understand their benefits and impacts, and by implementing key system demonstrations to validate the analyses. Systems Analysis will be critical for making key decisions that define the R&D objectives, milestones, and deployment activities of both the AFCI and Gen IV programs. As a result, these two programs have established a common systems analysis activity to provide the central linkage to integrate the two programs.

The Systems Analysis activities described in this plan are those funded through AFCI. For completeness, the activities supported by Gen IV are briefly mentioned in this plan. However, funding is not shown for those activities.

Systems analyses are performed on systems or subsystems in order to understand their behavior and impacts under various scenarios. The results primarily aid decision makers in selecting the best fuel cycle and reactor technologies and in formulating deployment strategies for them. Through systems analysis, technologies and strategies are optimized to make the best progress toward the long-term AFCI goals of reduction of waste volume, toxicity and repository cost, as well as the Gen IV goals of sustainability, economics, safety, reliability, proliferation resistance, and physical protection.

The Systems Analysis activities will be organized and performed by a multi-laboratory team known as the systems analysis working group and its transmutation subgroup. These groups will be comprised of representatives from the national laboratories (ANL, BNL, INEEL, LANL, LLNL, ORNL, SNL, and WSRC), under the overall leadership of the INEEL. The working group will continually interact with the national technical directors of the functional R&D areas in AFCI and Gen IV Program, as well as with the system integration managers for their major systems.

5.4.2 Systems Analysis Goals and Objectives

In the intermediate term, the top-level objective for Systems Analysis is to enable key DOE decisions in FY 2007 on fuel cycles and technologies that best support the AFCI and Gen IV goals. In particular, analyses and validation data are needed to facilitate a Secretarial recommendation on the technical need for a second repository by the end of CY 2007. To achieve this objective, nearer-term objectives in FY 2004 & 2005 focus on preliminary studies of intermediate-term fuel technology options and on facility needs and alternatives. Systems analysis also supports Gen IV program decisions on preferred Gen IV systems and technologies, and the establishment of criteria needed for repository performance assessments, including definition of needed R&D to confirm criteria before the Secretarial 2007 decision.

Ten-Year Objectives

High-level ten-year objectives of the systems analysis function within the AFCI and Gen IV include:

- Develop deployment strategies for the best fuel cycles in the intermediate- and long-term that are based on economic, energy, environmental, and nonproliferation benefits of advanced fuel cycles, balanced by the understanding of its development costs and technology risks. This objective is primarily supported by the broad systems studies, as well as the transmutation system studies and integrated model application described below.

- Assess and optimize a preferred nuclear fuel cycle for the U.S., including major alternatives and options. This objective is supported by the transmutation system studies and integrated model application.
- Assess and optimize individual Gen IV systems for the purpose of comparison and technology selection. This objective is supported by the Gen IV System Studies.
- Assess transmutation systems to compare and optimize Intermediate-term and Long-term approaches. This objective is supported by the transmutation system studies and integrated model application.
- Assess performance for specific technology options and facility alternatives that support the program.

5.4.3 Systems Analysis Major Milestones

The Systems Analysis milestones are depicted in Figure 5-9.

FY 2004

- Prepare an initial report on repository benefits and options that may be achieved by the AFCI.

FY 2005

- Prepare an initial report on the key benefits and technology needs of an advanced fuel cycle for the U.S. focusing on repository benefits and needed R&D to reduce uncertainties to achieve benefits.
- Prepare an initial report on advanced fuel cycle deployment options, including cost/benefit analysis.
- Prepare an initial report on requirements of the Gen IV systems (and possibly other fast spectrum transmutation options) needing advanced fuel cycle development.

FY 2006

- Prepare an interim report on advanced fuel cycle deployment options, including cost-benefit analysis, and report on progress and comparative merits of alternative reprocessing technologies.

FY2008

- Support the end of CY 2007 goal of providing necessary information for a Secretarial recommendation on the need for a second repository by providing a final report on a recommended U.S. transmutation approach addressing options on the path, or paths, forward if a recommendation to delay or forgo the need in the foreseeable future is made.
- Prepare an initial report on the impacts of the Secretarial recommendation on potential path(s) to the future for the AFCI /Gen IV integrated systems.

FY 2009

- Prepare the final report on the impacts of the Secretarial recommendation on potential path(s) to the future for the AFCI /Gen IV integrated systems with detailed cost estimates of the R&D needed to support both impacts on the repository and the Gen IV deployment activity.

During the years FY 2011 - 2014 the systems analysis effort will be needed to define and implement the steps toward the long-term deployment of the preferred fuel cycle. Specific needs are to coordinate the results of the ongoing ESE with calculations of repository impact, as well as to assess the ongoing key technology demonstrations of Gen IV.

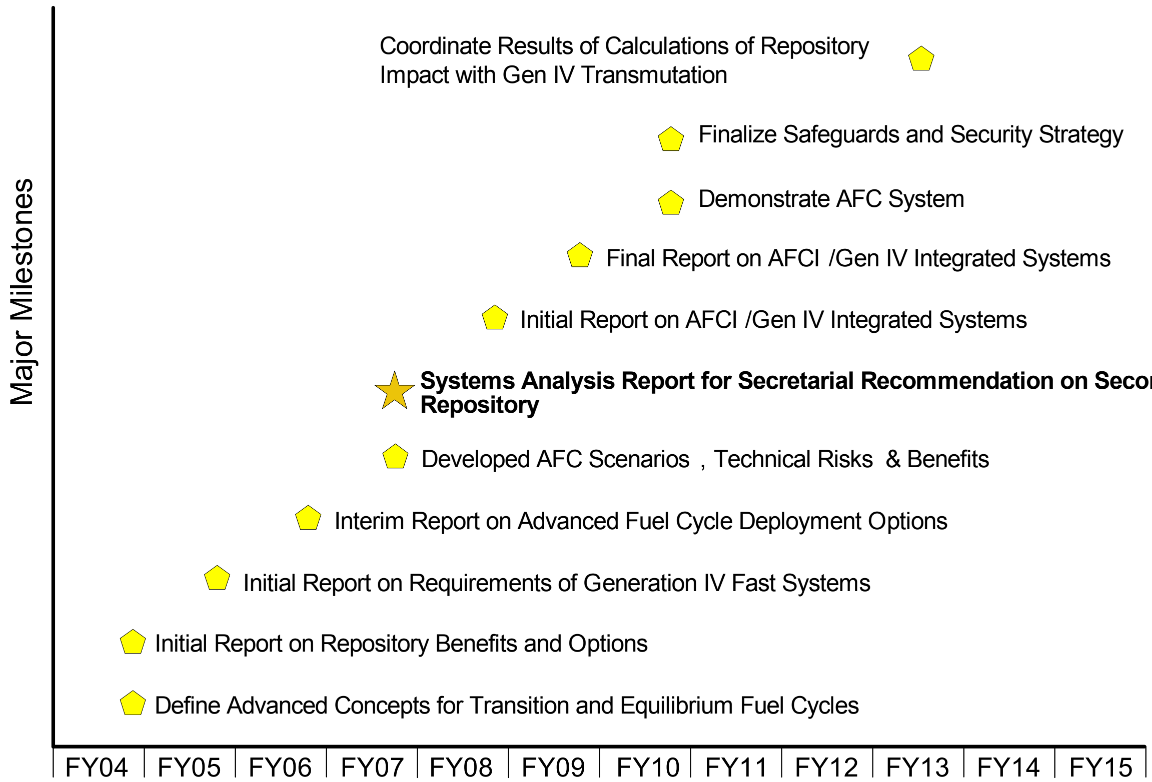

Figure 5-9. Systems Analysis Milestones

To accomplish these objectives, four levels of systems analysis activities have been defined; the highest level encompasses the entire system and its external influences while the lower levels provide increasing focus on individual subsystems, technologies, and facilities. The integration processes between AFCI and Gen IV, as well as between the various levels of AFCI systems analysis are iterative. That is, the higher-level analyses define the subsystems and their requirements, and the (lower-level) detailed subsystem analyses provide feedback for modifying and refining the higher-level analyses.

The systems analysis results will provide perspectives and answers to key policy and technology questions posed by future nuclear energy implementation strategies. The four major activities are:

Broad Systems Studies

These analyses support the definition of an integrated (and symbiotic) nuclear fuel cycle within broader economic, environmental, safety, proliferation, regulatory, and possibly social and political influences in a national or international context. These analyses explore the implications of nuclear energy deployment scenarios in the context of broader needs and policies. At this level, the objectives and milestones for the program can be examined and defined. The studies can also provide policymakers a broad, integrated perspective from which to define the desired role and implementation strategies for nuclear energy in the future. In addition, these studies can involve stakeholders and help to communicate and seek consensus on program objectives. These broad systems analyses typically consider the time-dependent behavior of the systems with simplified representations of parameters for resources, energy demand and production, fuel recycling, waste storage and disposal, etc. These studies depend on input from the more detailed integrated nuclear systems studies, individual Gen IV nuclear systems studies, and specific technology assessments.

Broad Systems Studies consist of two primary elements: Nuclear Futures and Industry Interactions. The Nuclear Futures activity executes the broad systems analyses that serve as a basis for the more detailed analysis activities conducted by other systems analysis activities. These studies are iterative in that they both incorporate results from more detailed analyses and define scenarios that guide the future development of these more detailed studies. The Industry Interactions activity is structured to stimulate high-level AFCI interactions with industry. These interactions will be focused on providing guidance and review of program assumptions in order to maximize the relevance of the AFCI to industry.

Transmutation System Studies and Integrated Model Application

Transmutation System Studies provide systematic analysis of the potential of existing and future reactor systems for transmuting transuranic elements and certain long-lived fission products. The first objective of transmutation studies is to develop a set of criteria against which to evaluate candidate fuel cycle options. These criteria will allow an objective definition of the potential benefits of each candidate. The second objective of transmutation studies is to establish a systematic comparison between all candidate fuel cycle options available for transmuting key isotopes: each option will be evaluated for feasibility and practicality, benefits and costs, useful implementation, and practical limits. The third objective of the transmutation studies is to support detailed technical analyses of the most promising technologies to assess key feasibility issues and support their licensing case.

Integrated Model Application considers an integrated nuclear fuel cycle subject to a number of assumptions about the demand for nuclear energy, availability of infrastructure and resources, and other key influences. The integrated nuclear fuel cycle consists of the symbiotic mix of reactors and recycling facilities, and is not limited to just one type of reactor and recycle technology (as in the next section). The integrated cycle includes all aspects of the cycle from mining through energy conversion to waste disposal. In this way, integrated studies can explore the implications of symbiotic fuel cycles combining thermal and fast spectrum reactors. The analyses employ detailed models of reactor irradiation to define the isotopic content of discharged fuel and the impact of recycling on neutronics and performance. The separations processes are modeled to determine material flows and characteristics for all material and waste streams. The repository is also modeled to assess future storage and waste forms along with transmuter, recycling, and interim storage options. Provisions can also be made to analyze costs, dose/risk to workers or the public, and other parameters. Optimization of the system leads to the definition of requirements and/or desired performance levels for transmuters, fuels, energy conversion, separations, storage and disposal. It also helps to identify interface requirements between the mix of transmuters, recycle facilities, and other subsystems.

Transmutation analyses will continue the studies initiated in FY 2002 and expand the work to ensure that intermediate-term and long-term analyses will provide the information necessary to support an FY 2007 decision on the optimum path forward for transmutation in the U.S. Integrated nuclear fuel cycle studies, focusing on intermediate-term issues, define the strategies and technology approaches to transition from the current once-through cycle to a treatment and recycle approach that meets waste reduction objectives with acceptable economic and environmental impacts. Long-term studies address the further transition to a long-term, steady state closed fuel cycle, which provides increased sustainability and a reduction of the toxicity and lifetime of waste forms, as well as advances toward other Gen IV goals.

Gen IV System Studies

These studies address individual Gen IV systems, including all aspects of the cycle from mining through energy conversion to waste disposal. These studies include detailed models of reactor irradiation, energy conversion, separations processes, and other components of that system. They focus on analyzing system performance with substantial accuracy; results of these studies provide the basis for the evaluation of systems against Gen IV goals and the fast reactor technology down-selection milestone. The analyses can be used to define subsystem requirements and interfaces and to optimize the overall system. Results from these analyses can inform decisions on preferred Gen IV systems and technologies. It should be noted that Gen IV funds these studies, but they are carefully coordinated with related studies of the AFCI to provide an integrated view of the nuclear future.

Technology and Facility Assessments

These activities provide evaluation methods to assess the intrinsic safety, security and safeguards of fuel cycle systems and facilities concepts and designs. In the near-term, safety studies will focus on development of a standard basis for evaluations through assessment of existing approaches and historic data on industrial and nuclear operations, and testing of the methodology on specific events and facilities. Security and safeguards studies will primarily interact with the Nonproliferation Review Committee and the Generation IV Proliferation Resistance and Physical Protection Expert Group to establish methodology. The validated methodologies will then be available to inform decisions on preferred technology and facility options for both the AFCI and Generation IV programs. As more of the higher-level decisions are made, this activity will be refocused to support more detailed program decisions.

Systems Analysis Ten-Year Plan

The high-level, ten-year activities and milestones for systems analysis are depicted in Figure 5-9.

5.5 University Programs

5.5.1 University Programs Overview

The mission of the Office of Nuclear Energy, Science, and Technology includes investment in human resources and infrastructure in the nuclear science and engineering and related fields. A key element of this investment is maintaining university research programs, research reactors, and associated infrastructure. Consistent with this mission, the AFCI supports a number of university activities, through the University Programs and as a part of the program's research activities. The elements of the university programs are described briefly in the sections that follow. The specific technical contributions of the University Programs to AFCI are included in the various technical sections of this program plan.

Beginning in FY 2004, the Department is integrating its Nuclear Energy Research Initiative (NERI) activity within its mainline R&D programs: AFCI, Gen IV Nuclear Energy Systems Initiative, Nuclear Hydrogen Initiative, and Nuclear Energy Technologies. As such, the NERI program will be accomplished in a distributed fashion within the nuclear energy R&D programs. The new approach to executing NERI research will retain the competitive solicitation and independent peer review critical to ensuring the pursuit of leading-edge technologies. NERI will be focused on integrating the nation's universities into the Department's nuclear energy R&D programs. A portion of AFCI funding will be applied to support peer-reviewed, university-based research in this manner.

5.5.2 University Programs Goals and Objectives

The goal of the AFCI University Programs element is to foster the education of the next generation of scientists and engineers who will support the growth of nuclear power as a vital part of the national energy future. More specifically, the AFCI program seeks to stimulate interest in training for technical roles in the development and application of advanced fuel cycles as a critical requirement for long-term, sustained nuclear energy. This objective is achieved by funding research and infrastructure upgrades at the universities.

5.5.3 University Program Elements

University of Nevada at Las Vegas. The University of Nevada at Las Vegas (UNLV) activity is designed to benefit DOE transmutation research and the University's goals to enhance student-focused and internationally recognized research programs. AFCI funds both research activities and infrastructure upgrades at the university. More than 50 students (currently 26 graduate, with Masters and PhDs, and 23 undergraduates) have been employed at UNLV in research projects and as support to the project administrators in the Harry Reid Center for Environmental Studies. These students represent several colleges at UNLV, including Health Sciences, Engineering, and Sciences, and several departments within those colleges. The research projects at UNLV are highly interdisciplinary, cutting across departments and even colleges.

UNLV activities are focused in the area of transmutation research and span a range of technology areas, including separations, fuel fabrication, accelerator design, and materials corrosion. To support these research efforts, the university is upgrading a variety of infrastructure including the establishment of a materials performance laboratory and a flow visualization system, installation of a lead bismuth test loop and upgraded machining capabilities. In addition, UNLV is nearing completion of a new Transmission Electron

Microscope (TEM) laboratory. This facility will allow researchers to analyze systems at the atomic level for elemental and chemical composition. The university continues to hire faculty to support the various research areas.

Idaho Accelerator Center. The Idaho Accelerator Center (IAC) is an organization at Idaho State University that provides facilities for research and education in charged particle accelerator applications in nuclear and radiation science. The purpose of the IAC is to study and develop applications of nuclear and radiation science, low-energy charged-particle accelerators, and related technology. It conducts research in four broad areas: 1) Nuclear Medicine/Health Physics; 2) Non-Destructive Evaluation, Assay, Elemental Analysis and Imaging; 3) Fast Diagnostic Instrument Development and Testing; and 4) Basic Nuclear Measurements and Radiation Effects. Most of the research at the IAC is done in collaboration with other organizations including national laboratories, other universities and the private sector.

The IAC operates more accelerators and more kinds of particle and radiation beams than any other university in North America. Currently operating accelerators at the IAC include a 28 MeV pulsed electron linac with pulse widths as short as 10 picoseconds, a 40 MeV electron linac driven neutron source, a portable 2-12 MeV electron linac, a 6-MeV and several 4 MeV electron linacs, two positive-ion Van de Graaffs for proton, and light-ion beams, several high-intensity X-ray machines and an unique accelerator/laser Compton back-scatter nonenergetic photon source. In addition, there is a ultra-high current electron accelerator, ISIS (10MeV, 10kA) being commissioned in a new building at the IAC campus. Work on this facility will be complete in mid FY 2005. While this machine is part of a DOD project there is little doubt that it can play a significant role in future DOE work, particularly in materials research.

In the Reactor-Accelerator Coupling Experiments (RACE) Project of the U.S. Advanced Fuel Cycle Initiative (AFCI), a series of accelerator-driven subcritical systems (ADSS) experiments will be conducted at the Idaho State University's Idaho Accelerator Center (ISU-IAC), at the University of Texas (UT) at Austin, and at the Texas A&M University. In these experiments, we will use electron accelerators to induce bremsstrahlung photon-neutron reactions in heavy-metal targets; this source of about 10^{12} to 10^{13} neutrons per second will then initiate fission reactions in the subcritical systems. These accelerator-driven nuclear systems will include a compact, transportable assembly at ISU and TRIGA reactors at UT-Austin and Texas A&M. Each experiment will be progressively more complex, with higher neutron multiplication and higher power. By the end of FY04, the RACE Project will involve 5 to 6 universities, about 10 faculty and 10 students, an international Technical Advisory Group, and technical staff at Argonne and Los Alamos National Laboratories. The three-year budget for this project is less than $2 M, mostly from ISU and UNLV AFCI funds.

AFCI Fellowships – University Research Alliance. The University Research Alliance (URA), located in Amarillo, Texas) is a consortium of Texas universities, which manages the AFC University Fellowship Program (AFC UFP) for DOE/NE. The University Fellowship Program is intended to support top students across the nation in a variety of disciplines that will be required to support transmutation research and technology development in the coming decade. In the first two years, 20 Fellows were selected from highly qualified applicants. In April of 2001 and 2002, the Fellowships were awarded to students to attend graduate schools at 16 universities. The AAA and AFCI Fellows work on a variety of topics while they conduct research for their Masters theses and degrees. Selection of new students for FY 2003 Fellowships was suspended because of a shortfall in funding and a delay in the passage of the FY 2003 budget. The program was resumed in FY 2004.

The URA continues ongoing detailed management of the Fellowship Program, including ensuring that Fellows receive stipends in a prompt manner, that special needs are addressed and accommodated appropriately, and that students stay on track for completing their fellowships in a timely manner. In addition to these tasks, the URA worked with each of the 2002 Fellows and their universities to ensure that financial aspects of enrollment, tuition, and stipends were smooth and to ensure prompt reimbursement to the students for appropriate and allowable expenses. A call for 2004 fellowships was issued in January 2004 and it is anticipated that these new fellowships for the fall 2004 semester will be announced in April 2004. The selected fellows are offered an opportunity for summer work at a national laboratory conducting AFCI R&D, where they receive assistance in selecting a relevant thesis topic. Approval of the thesis subject by AFCI staff is a requirement of the fellowship.

5.6 International Collaborations

A major element of the AFCI approach to achieving its mission is a robust cooperative program with international partners interested in the development of nuclear technology. To date, DOE has entered into nuclear energy research and development cooperative agreements with the French Commissariat a L'Energie Atomique (CEA), the Swiss Paul Scherrer Institute (PSI), and the European Commission (EC) and estimates that it has obtained analytical and experimental data worth over $100 million to the AFCI program, as well as permitting us to partner in fuels and materials related experiments that are not possible anymore in the U.S. DOE will continue to exchange information with these international partners and is exploring the potential for similar cooperation with other countries such as Japan and Korea. This effort will continue to leverage the resources of the U.S. and other countries with advanced fuel cycle development programs and expedite demonstrations of treatment and transmutation technologies. One method under development for expanding the international nuclear cooperation is the International Nuclear Research Initiative (I-NERI) program in which we will seek partners who are performing activities similar to those in our existing programs. Possible INERI collaboration areas include separations, fuels, transmutation, and systems analysis: separations involving small scale demonstrations; fuels and materials involving long-term irradiation; and advanced transmutation facility design and development. The technologies affected by our international cooperation in the areas of fuels, materials, and separations are vital to slowing down and eventually reducing the accumulation of plutonium and other radiotoxic materials that need to be disposed of as high-level waste—a goal common to all our international partners.

6.0 PROGRAM MANAGEMENT

6.1 Organizational Structure

The DOE Office of Nuclear Energy, Science, and Technology (DOE/NE), shown in Figure 6-1, is responsible for leading the federal government's investment in nuclear science and technology. The nuclear energy program represents the core of the U.S. Government's expertise in nuclear engineering and technology. The DOE/NE is responsible for maintaining the nation's access to diverse and environmentally responsible sources of energy and advancing the country's economic and technological competitiveness. As discussed previously, AFCI and the Gen IV Nuclear Energy Systems program are closely linked. Gen IV is an international initiative for identifying, developing, and demonstrating one or more new nuclear energy systems offering advantages in the areas of economics, proliferation resistance, safety and reliability, and sustainability, with a deployment decision targeted for 2030. DOE/NE has established a structure to coordinate the R&D (R&D) efforts of both programs. Within this structure, AFCI has been organized to maximize and leverage technical functional expertise, while enhancing communication between program participants through systems analysis and technical integration. Figure 6-2 shows the DOE/NE program office organization.

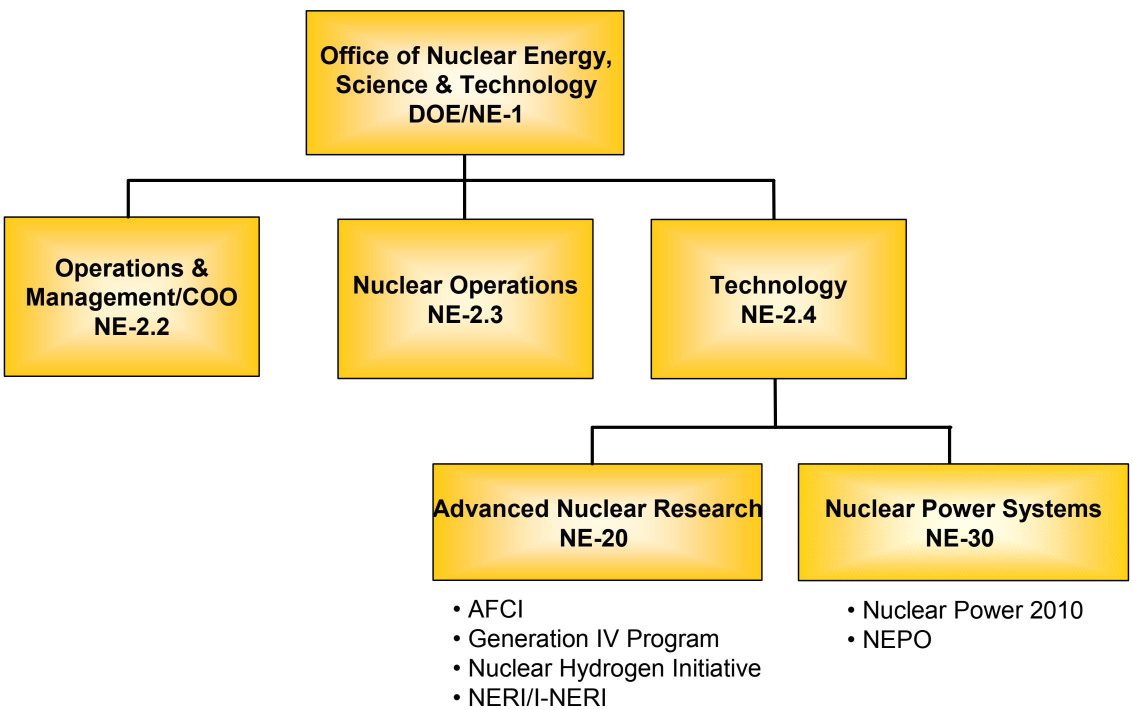

Figure 6-1. Nuclear Energy Organizational Structure

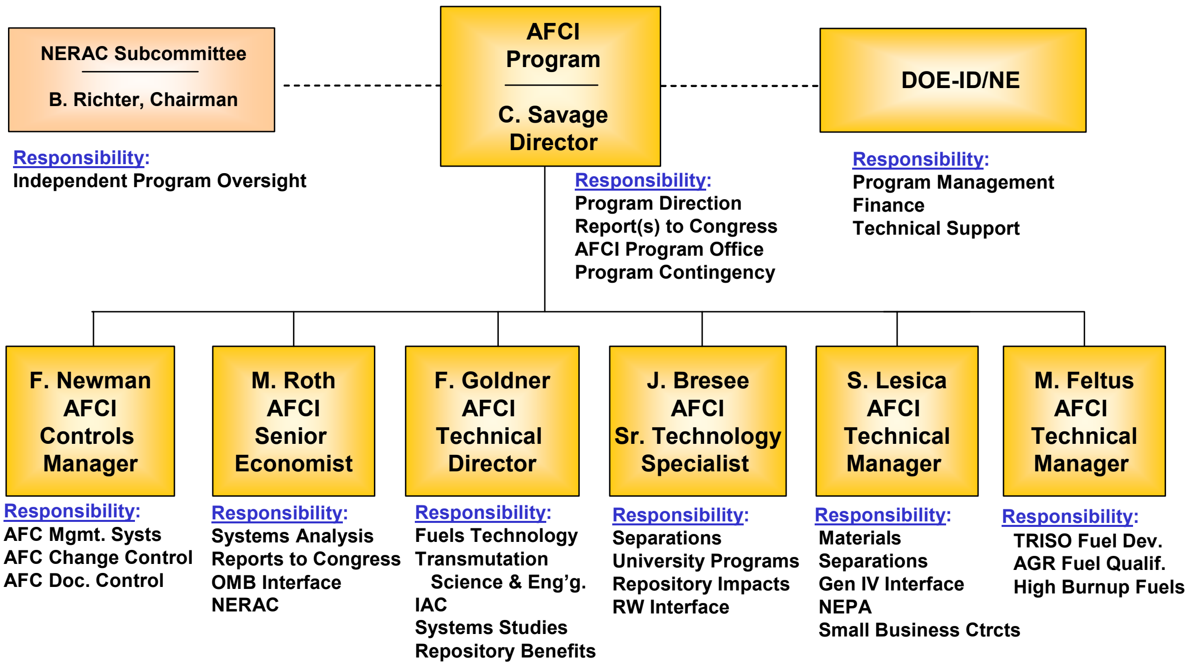

Figure 6-2. AFCI Program Office Organizational Structure

Roles and Responsibilities

AFCI and Gen IV have an integrated management structure, sharing a common systems analysis function. DOE/NE and AFCI participants each have specific roles and responsibilities in the management and execution of the program. These include technical integration, systems analysis, and national technical director for each technology development element of AFCI – fuels, separations, and transmutation science and engineering. System Integration teams are established to address major system and facility issues for AFCI and Gen IV. A schematic diagram of this functional structure and organization is shown in Figure 6-3. Specific roles and responsibilities for each of these functions are listed below.

Office of Nuclear Energy, Science, and Technology (including NE-ID). Essential programmatic functions include, but are not limited to the following:

- Establish program policy and issue programmatic guidance.
- Manage programmatic planning and processes.
- Develop budgets and distribute program funds to participants.
- Establish performance measures and conduct annual performance reviews.
- Review, comment on, and give final approval to all tasks.
- Manage the development of a programmatic strategic plan.
- Coordinate, review, comment on, and approve final AFCI Plan.
- Develop program requirements, standards, and procedures.

- Provide program interface to external organizations including Office of Civilian Radioactive Waste Management (OCRWM), National Nuclear Security Administration, Department of State, Nuclear Energy Research Advisory Committee (NERAC), the Advanced Nuclear Transformation Technology (ANTT) sub-committee of NERAC, and collaborative international entities.
- Evaluate and assess program progress and interface with the national technical directors.
- Establish, manage, and approve international agreements and foreign travel.

Systems Analysis. The systems analysis function develops and applies tools to formulate, assess, and steer program activities to meet programmatic goals and objectives, including the following:

- Integrate R&D by formulating recommendations to focus program development direction.
- Integrate program level systems analysis for both AFCI and Gen IV.
- Deploy system tools to develop recommended priorities for technology development.
- Perform analyses to inform decisions on fuel cycle and reactor technologies.
- Formulate technology deployment strategies.

At the request of the Chairman of the NERAC ANTT subcommittee, a Transmutation Systems Analysis sub-group, reporting to the national Technical Director for Systems Analysis, was established to ensure that transmutation research requirements are properly identified and prioritized.

Technical Integrator. The Technical Integrator works in close coordination with DOE/NE program management and the national Technical Directors to:

- Coordinate and implement technical program guidance.
- Coordinate, facilitate, and manage semi-annual program technical review meetings and all other major AFCI meetings.
- Develop monthly and quarterly reports.
- Coordinate with Program Controls to track tasks to ensure that scope, cost, and schedule are met, including milestones. Alert the DOE/NE to all potential problems, technical and programmatic issues.
- Develop and update (as necessary) the AFCI Ten-Year Program Plan.
- Coordinate development of AFCI long-range technical planning.
- Develop and maintain external communication products for AFCI, such as congressional reports, fact sheets, displays, and Web pages.
- Develop and update communication plan.
- Coordinate AFCI conference participation and publications.
- Identify, develop, and monitor technical and programmatic risk mitigation strategies.
- Coordinate technical reviews and assessments.

National Technical Directors. The National Technical Directors manage technical R&D activities, including:

- Develop, coordinate, and execute targeted functional area research, including the implementation of the AFCI Ten-Year Program Plan.
- Direct and develop proposed tasks and manage scope, cost, and schedule of the functional technical area.
- Support product team efforts to ensure integration of product requirements into the R&D activities.
- Coordinate with international partners in the conduct of mutually beneficial R&D activities.

System Integration Teams. System Integration teams are needed to address the technical issues and develop R&D plans that identify the milestones and deliverables that support the innovative systems and new facilities with key R&D activities. System Integration teams are identified for each Gen IV system, as well as the key AFCI facilities such as those dedicated to large-scale spent fuel treatment and fuel refabrication. System Integration managers are identified that bring substantial technical credentials and leadership. The system integration teams:

- Define major AFCI facility and Gen IV system requirements.
- Develop product-specific R&D technology roadmaps using interdisciplinary teams.
- Analyze and advance the progress of the system or facility each year.
- Support the major program decisions on the selection of their system or facility.

AFCI Management Processes

The AFCI R&D Program is managed according to the principles of DOE Order 413.3, Program, and Project Management for the Acquisition of Capital Assets.

On an annual basis, DOE/NE provides draft budget guidance to the national laboratory participants based upon technical activities outlined in this Plan, which will be updated as necessary. Upon receiving the draft budget guidance from DOE/NE, each participant develops draft work packages that include cost, schedule, and scope by individual Work Breakdown System (WBS) elements consistent with this Plan. The National Technical Directors and the Technical Integrator review the draft work packages for completeness and overall program integration. The draft work packages are then reviewed and revised if necessary by DOE/NE, who then distributes final fiscal year budget guidance for each participant. Program participants revise and finalize their work packages based upon the budget guidance. The National Technical Directors and the Technical Integrator again review the final work packages for completeness and integration, and DOE/NE reviews them for final approval. Once DOE/NE approves the work packages, they establish the cost, schedule and technical baselines for each participant and establish the overall integrated program baseline.

A program controls system has been established to monitor the performance of work packages once they are approved. The status of each work package is evaluated monthly by the relevant NTD, the HQ lead, the Technical Integrator, and the Program Controls group to assess performance. For work packages where the variance from the baseline exceeds a threshold, a more in-depth evaluation is initiated and a corrective action plan initiated as necessary.

The AFCI program also has a DOE-managed university grants program that competitively awards selected fellowships at the Masters and Doctoral level to college and university students in fields of study directly related to the AFCI program. The management of the Fellowship program is described in Section 5.5.

The AFCI program is also a participant in the new approach to NERI. The DOE technical managers and the NTDs have responsibilities for identifying potential university projects, evaluating proposals, and selecting projects for funding (see Section 5.5.1). AFCI also leverages its work packages into collaborations with international partners, using AFCI-specific and INERI bilateral agreements (see Section 5.6).

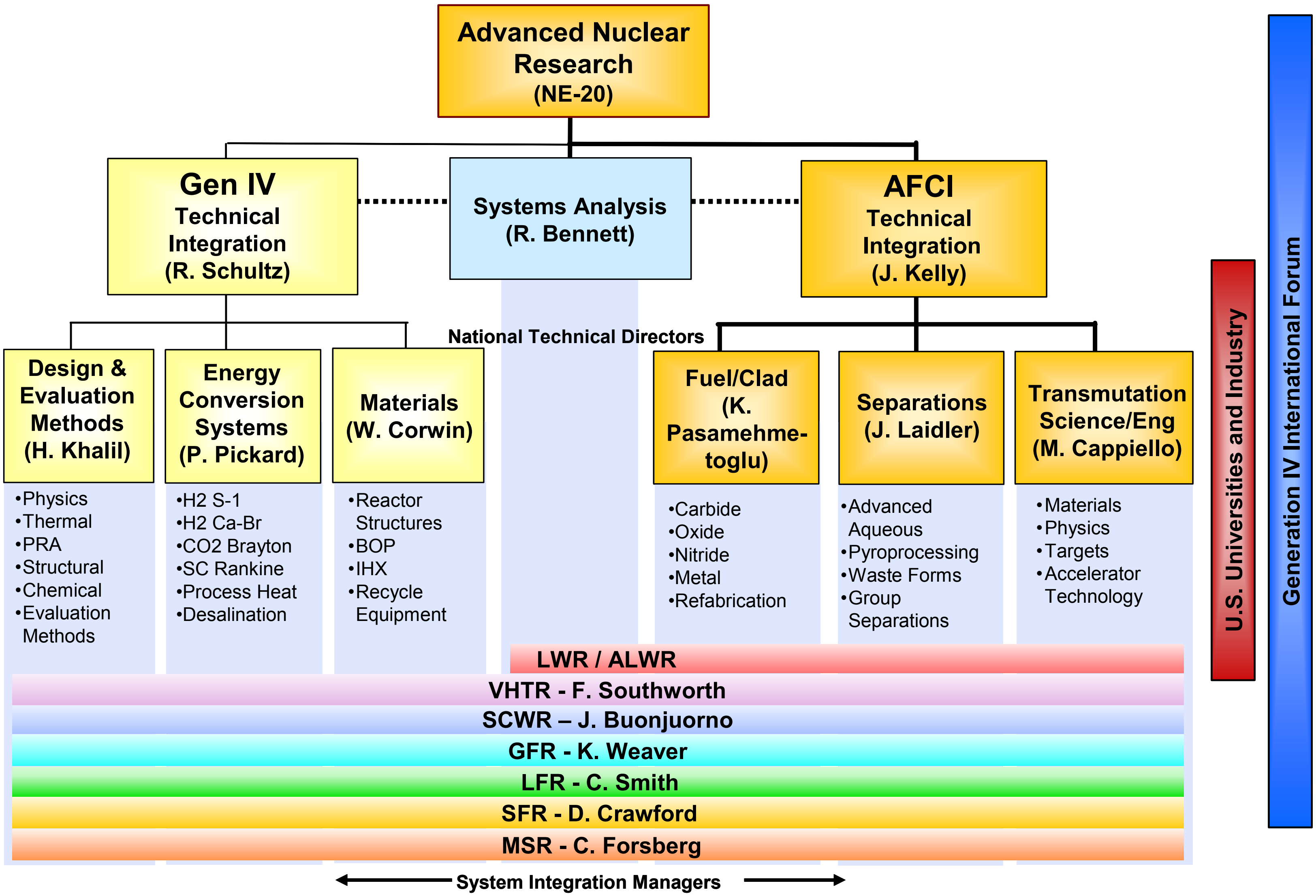

Figure 6-3. Integrated Gen IV and AFCI Organizational Structure

The National Technical Directors and the Technical Integrator monitor program performance against the established baseline. Changes to the baseline must be approved through the AFCI Change Control Process. These baselines also support the development of each participant's performance measures and metrics, which are used in the annual 360-degree performance evaluations.

In addition to this program plan, DOE/NE has developed an AFCI Program Management Plan to specifically address the manner in which this program is managed and management-related issues identified through the Office of Management and Budget Program Assessment Rating Tool (PART) and Applied R&D Investment Criteria exercises.

6.2 Key Program Assumptions, Uncertainties, and Risks

A number of critical assumptions form the planning basis for AFCI. Associated with each assumption, there is a degree of uncertainty, which represents some risks to the program. These risks include both technical risks and programmatic risks.

6.2.1 Assumptions and Uncertainties

Planning Budget

This plan assumes a FY 2004 budget of $68 million, based on the Congressional appropriation enacted in December 2003. The budgets for FY 2005 through FY 2014 will be based on the required levels. It also assumes support for a robust Gen IV Program, including sufficient funding to develop Generation IV fuels.

Major Facilities Schedule

DOE will lead the effort to perform the R&D and engineering scale experiments and demonstrations to achieve sufficient technical readiness levels and provide industry with a high level of confidence in production-scale facility construction costs and schedules. DOE will participate with industry in facility design activities through preliminary design in order to achieve the desired confidence level. DOE expects industry to take the lead in construction and operation of the production facilities needed to implement Gen IV technologies, including fuel cycle facilities. Actual deployment dates will depend on industry's needs and economic factors, the same factors that will decide the future of nuclear energy in the U.S.

Spent Nuclear Fuel Generation Rates

The current planning basis for AFCI assumes that spent nuclear fuel discharge rates from domestic power plants will remain relatively constant for the next 30 years. Large changes in this discharge rate, such as those associated with new power plant construction will require reexamination of anticipated impacts.

Transition to Proliferation-Resistant Fuel

The transition to proliferation-resistant fuel will require investment to implement changes in the nuclear power industry. The program assumes that the proliferation-resistant fuel will have characteristics that provide the utilities incentives to make use of this fuel in their existing LWR systems.

Gen IV Concept Selection

It is assumed that at least one fast spectrum Gen IV reactor concept will be developed to provide the transmutation performance necessary to achieve the goals of AFCI Gen IV fuel cycle.

Legacy Cleanup Costs

The legacy cleanup costs associated with AFCI testing activities have not been included in cost estimates provided in this plan.

6.2.2 Technical Risks

Separations Performance

Although the chemical processes proposed for the spent fuel treatment facility are relatively well understood, achieving the goals of AFCI requires that this facility operate with very high separations efficiency and low losses. Technical risk is associated with moving from small-scale technology demonstrations to a production-scale plant. The role that intermediate (engineering)-scale demonstrations can serve to mitigate this risk is currently being examined.

Proliferation-Resistant Fuel Performance

Some technical risk is associated with the proposed fuel form for the AFCI transition fuel cycle activity. This risk is associated with adding an additional constituent (neptunium and possibly other materials) to achieve the proliferation-resistant characteristics. At this time, the effect of this change in chemical composition on fuel performance has not been quantified. The risk associated with development and licensing of this fuel is considered moderate.

6.2.3 Programmatic Risks

Budget Allocation

AFCI has aggressive schedules so that it can provide time-critical credible technical options. Substantial stable long-term funding will be required to achieve this objective. It will be necessary for the program to continuously update its technical plan based on available funding levels.

Evolving National Policy

The treatment of spent nuclear fuel involves activities regulated by both national and international policy. AFCI must monitor and/or recommend changes to these policies to ensure that proposed activities can be conducted within the requirements imposed.

Risk Mitigation

A major role of the Technical Integrator, working with DOE and the national Technical Directors, is to identify, develop, and monitor mitigation strategies for both technical and programmatic risks associated with the AFCI program.